Climate Change and Agriculture: Impacts to Prices and Agricultural Production

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Abstract

Climate change is expected to greatly impact the global economy in the future, but uncertainty abounds regarding the magnitude of those impacts. For agriculture, the future is expected to consist of both supply pressures (changes to crop and livestock yields/productivity and shifts in the suitability of land to produce a certain crop) and demand pressures (a larger and richer population). The literature has typically considered supply and demand individually, but in this work, we attempt to combine them to provide a fuller picture of what agriculture might look like in 2050 due to climate change. To do so, we combine information on crop and livestock yield/productivity changes with estimates of how land might change by shifting Agro-Ecological Zones (AEZs). We use these supply changes in a computable general equilibrium (CGE) model, along with potential demand changes to estimate the impacts of climate change on agricultural production and prices. We also discuss the distributional impacts of climate change on agriculture and food security. Given that the global poor could be the most impacted by climate change, we focus our results on examining how Africa, in particular, is affected.

1 Introduction

Climate change is the defining issue of our time due to the threat to food production from shifting climate patterns, flooding from rising sea levels, and heat stress (United Nations 2023). And climate change is expected to impact the poor hardest. Woetzel, Pinner, and Samandari (2020) examines 105 countries and finds that lower-income countries are more at risk than wealthier countries as they often have a higher share of GDP tied to agriculture and/or rely more on natural capital—both of which are vulnerable to climate change. In addition, poorer countries are likely to have less capacity to adapt or help mitigate the effects from climate change (Abeygunawardena et al. 2004; Alizadeh et al. 2022; Kwon et al. 2016). Hallegatte (2016) also note that climate change can increase poverty and impact food security by affecting those who are not poor but vulnerable—for example, a drought decimating a herd of cattle.

One reason for the importance of agriculture in climate change is that the global population is expected to expand (UNDESA 2022 states that it could reach 11 billion people by 2100)—thus more food will be necessary. At the same time, incomes in many developing countries have been increasing, leading to a greater demand for animal-based products that in turn require crops (e.g., maize) and rangelands for feed; Komarek et al. (2021) project that total global demand for livestock-derived foods in 2050 will be 38 percent greater than that for 2020. The need for more food, and for animal-based products, puts pressure on the agricultural sector to meet those changes; but the amount of resources available to produce food are finite and are under pressure from climate change. Ortiz-Bobea et al. (2021) note that climate change has already slowed productivity[1]—mainly as a result of declining yields in tropical locations.[2] For future yields, estimates from the Agricultural Model Intercomparison and Improvement Project (AgMIP) indicate that shifts in global

[1]The terms 'productivity' and 'yields' are often used interchangeably, but Fuglie (2021) notes that there are differences, such as that productivity, as measured by total factor productivity (TFP), includes productivity impacts not just on land, but also on other resources. He also notes that most assessments of the productivity effect of climate change on agriculture have focused on yields, especially to crops.

[2]Specifically, they find that agricultural TFP decreased by 21 from 1961 to 2015, impacting warmer regions such as African and Latin America and the Caribbean the most. In fact, R. Mendelsohn, Dinar, and Williams (2006) note that it is the location where the global poor lives that determines the distributional impacts of climate change.

crop productivity due to climate change could happen sooner (within the next 20 years) than previously projected (Jägermeyr et al. 2021). Additional studies (e.g., Challinor et al. 2014; Porter et al. 2019; Zhao and Asseng. 2017) also conclude that rising temperatures will harm global crop yields.

In addition to crops, a changing climate could threaten livestock production if temperatures rise to those predicted by climate scientists. Heat stress, when temperatures are higher than an animal's thermoneutral zone, can affect weight gain, milk yield, and fertility (P. Thornton et al. 2022). A changing climate can also indirectly affect livestock production by reducing the quantity and quality of food available as feed, increasing competition for fresh water, and spreading disease-causing pathogens (Rojas-Downing et al. 2017). Land-based production systems in which livestock obtain most of their food from grasslands and crop residues may be particularly vulnerable to climate change because animals are exposed to the weather, and producers may be limited in their adaptive capacities (Kwon et al. 2016). Literature has pointed out that livestock could be impacted differently than crops, with R. O. Mendelsohn and Massetti (2017) noting that livestock can tolerate higher temperatures than crops. But they note that the yield or productivity of livestock could still be heavily impacted by climate change.

The focus on yields/productivity to demonstrate the importance of climate change on agriculture is understandable as the world is running out of arable land and climate change is further reducing land suitable for agriculture (Schneider, Zabel, and Mauser 2022). But a changing climate also has the potential to impact another aspect of agricultural production—acreage planted. Climate change can both affect the extent of land available, and the productivity of that land—i.e., some crops are most efficiently grown in certain area based on favorable temperature and precipitation. In terms of acreage planted, the United States Global Change Research Program (USGCRP) (2018) notes that climate change can influence land cover, such as through the loss of land, drought causing land to be left fallow, or through changes in yields. In addition, King et al. (2018) notes that climate change is likely to result in higher temperatures, which could lead to a northward shift of warmer climate.

Much of the research on potential changes to crop and livestock yields/productivity assumes that land stays the same under the different climate conditions, yet it is likely to change. Research that examines how land might change under future climate often does so using the Agro-ecological Zone (AEZ) classification.[3] For example, Kurukulasuriya and Mendelsohn (2008) use a multinomial logit to predict the probability of AEZs changing in Africa under a harsh and mild future climate scenario (using precipitation and temperature). Kala, Kurukulasuriya, and Mendelsohn (2012) also focus on Africa and estimate the potential for shifting AEZs for three climate scenarios. One reason for the focus on Africa is because a shift in AEZs could make some areas unsuitable for agriculture altogether—especially in the tropics. For example, Schneider, Zabel, and Mauser (2022) estimate that highly suitable arable land in Africa will decrease by 51 percent while marginally suitable arable land will increase by 14 percent. Lin et al. (2013) use a global climate model (known as HadCM3) to estimate how AEZs might shift in China. Di Vittorio project future AEZs using a climate model (known as GCAM) for 2071—2100. However, one deficiency with many of these papers is that they do not consider the economic implications of shifting AEZs.

In this work, we pull together information from three areas affected directly by climate change: changes in crop yields, livestock yields, and shifting land use patterns to consider how climate change could affect agricultural production and economies, leading to changes in food prices and state of food insecurity. For crop yields, we use the latest estimates from the Global Gridded Crop Model Intercomparison (GGCMI)—which projects what future yields might be for corn, rice, soybeans, and wheat. For livestock, we use a biomass simulation model called G-Range along with yield functions to simulate future changes in livestock productivity, following similar climate change assumptions as the GGCMI analysis. To simulate potential shifts in agricultural land use patterns, we use NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) daily global forecasts to re-categorize each global AEZ based on forecasted changes in each AEZ for each country. Using these yield and land change projections, we then consider how climate change from 2017 to 2050 will impact agriculture production and the availability of food using a computable general equilibrium (CGE) model. CGE models have been extensively used in estimating potential climate impacts, as they can incorporate

[3] An Agro-ecological Zone is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use. It is a common land classification that can be used across a variety of models.

information from our three areas impacted directly by climate change to estimate the potential changes to production, prices, trade, and macroeconomic factors. Because the poor could be the most impacted by climate change, we focus our results on examining how Africa is affected in terms of food prices and agricultural production. This is a continent that is expected to be hardest hit by climate change. Already, climate change has reduced overall productivity growth in Africa by 34% since 1961 according to one estimate (Ortiz-Bobea et al. (2021)).

2 Crop Yields

To consider how crop yields could affect agricultural productivity in the future under climate change scenarios, we use data from Jägermeyr et al. (2021)—which provides the latest estimates of yields for corn, rice, soybeans, and wheat based on climate models currently used by the Coupled Model Intercomparison Project (CMIP-6). The data is based on estimates from global climate models (GCMs) and global gridded crop models (GGCMs) for two different climate scenarios: Representative Concentration Pathways (RCP) 2.6, Shared Socioeconomic Pathways (SSP) 1—which is a representative scenario of optimistic climate mitigation policies; and RCP 8.5, SSP 5—a scenario that projects high emissions. For this work, we only focus on RCP 8.5, SSP 5, presenting an upper bound on likely changes to crop yields. We present some trends in how yields are estimated to change over time, especially among major producers of these commodities. Note that Jägermeyr et al. (2021) highlight that crop yields will be most negatively impacted by around 2070–2080, but we consider the changes to 2050 as this is the year most climate change induced forecasts focus on and define as "middle of the century" (e.g., R. Mendelsohn, Nordhaus, and Shaw 1994; Burke and Emerick 2016; Ortiz-Bobea and Tack 2018). Our CGE model reference year is 2017, so all crop yields described below consider the change from 2017 to 2050.

2.1 Corn

The GGCMI ensemble mean—that is, the average yield across the twelve crop models and five climate models—indicate that climate trends are already reducing corn yields (Figure 1), although actual corn yields have increased over time due to changes in technology. The major producers (in terms of land allocated to corn in 2021) were China (43.3 million hectares), the U.S. (34.5 million hectares), and Brazil (21.8 million hectares). Together they accounted for 48 percent of the land allocated to corn for the world. U.S. yields have been much larger than those for Brazil and China. According to FAS (2023), U.S. yields in 2021 were 11.1 t/ha, while Brazil yields were 5.3 t/ha and China's were 6.3 t/ha. But climate change is estimated to impact U.S. corn yields more than those for Brazil and China. The data indicate that climate trends will reduce U.S. corn yields by 24.8 percent for 2050 relative to 2017. This is larger than the global average decrease of 15.4 percent. In China, yields are projected to fall 12.1 percent due to climate change, while in Brazil they are projected to increase 3.9 percent.

2.2 Rice

Figure 2 presents rice yield projections. The first thing to notice is that projections for rice yields are much less variable than they are for corn. This is true for the global average yield, as well as the yield for major producers China, India, Bangladesh, and Indonesia. Although India allocates more land to rice cultivation than China, China has higher production due to its higher-than-average yields. This is partly because China applies greater quantities of fertilizer than other countries (Naher et al. (2019)). The other major difference for rice yield projections is that they are positive, globally and for major producers. The GGCMI shocks indicate that, similar to the case with corn production in the U.S., China maintains the largest yields, but these yields get a little closer to the world average as China is forecasted to have an increase in yields (5.9 percent) that is slightly smaller than the global average (6.1 percent). The yields for the other major producers also increase in India (5.4 percent), Bangladesh (1.5 percent) and Indonesia (6.7 percent); these numbers are not shown in the figures.

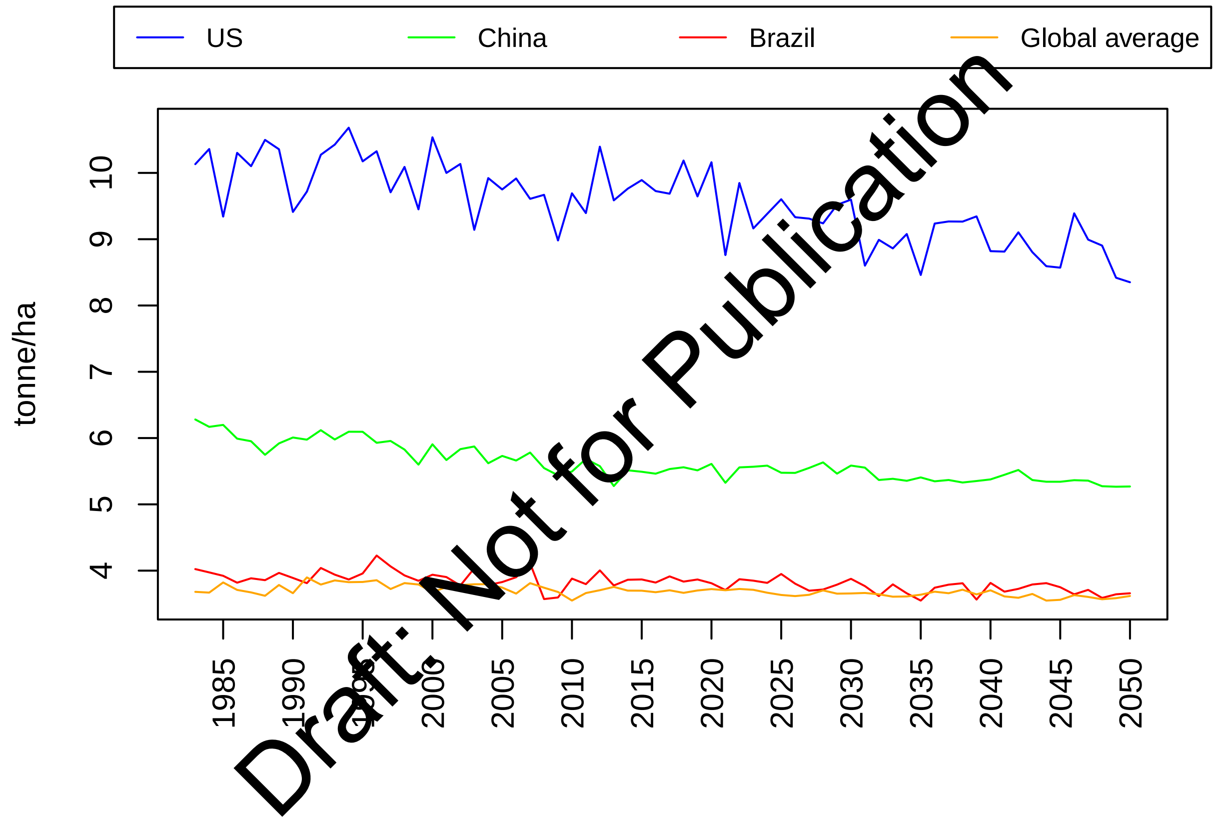


Figure 1: Estimated corn yields from GGCMI. Source: Jägermeyr et al. (2021). Notes: The estimated yield is the model ensemble mean across the twelve climate models and five crop models.

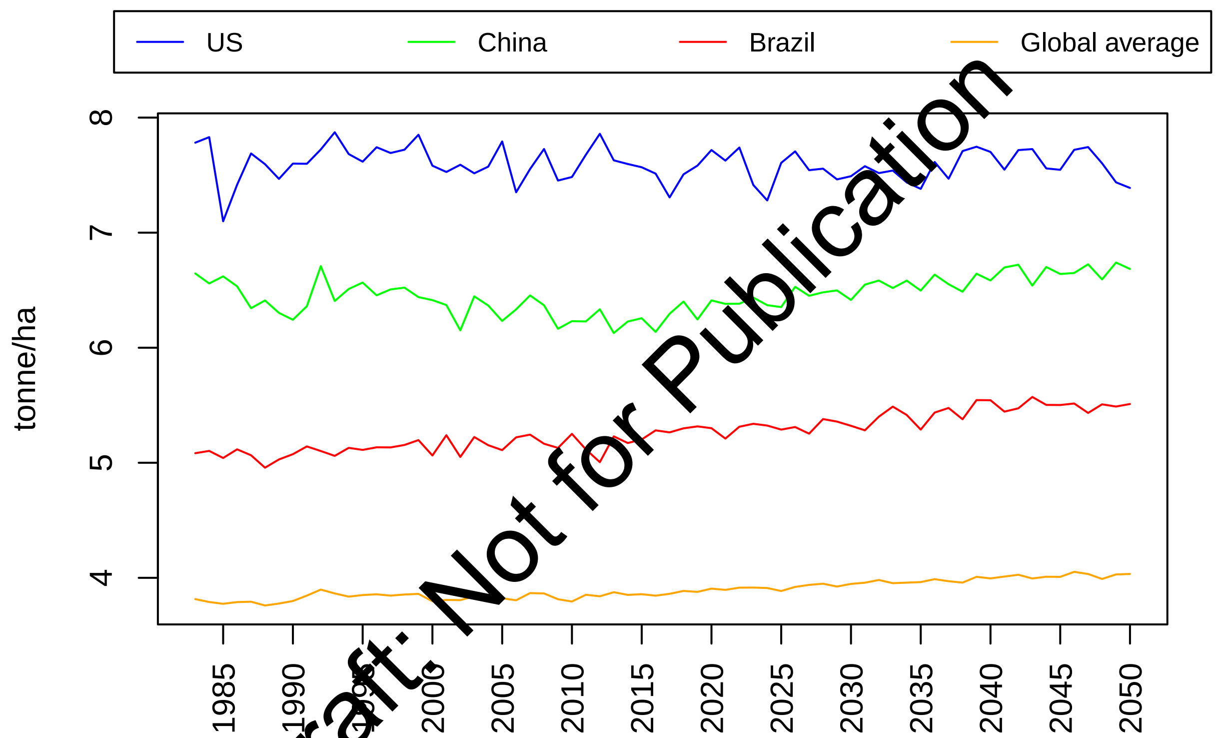


Figure 2: Estimated rice yields from GGCMI. Source: Jägermeyr et al. (2021). Notes: The estimated yield is the model ensemble mean across the twelve climate models and five crop models.

2.3 Soybeans

Soybeans are the oilseed that are produced the most, globally, accounting for 358 million tonnes (Mt) of the 607 Mt total oilseed production in 2021 (FAS, 2023). Figure 3 presents the projected changes in future soybean yields, with a decrease of 4.1 percent in 2050 relative to 2017. In 2021, the major producers (in terms of land allocated to soybeans) were Brazil (41.5 million hectares), the U.S. (34.9 million hectares), and Argentina (15.9 million hectares). Together they accounted for 70 percent of the land allocated to soybeans for the world, and 82.4 percent of production due to their higher yields than other producing countries such as India and China. Global soybean yield is projected to decrease as the yields for the two largest producers also decrease: Brazil (-0.9 percent) and the U.S. (-14.6 percent); although Argentina has an increase (13.2 percent). The numbers for Argentina are not shown in the figures.

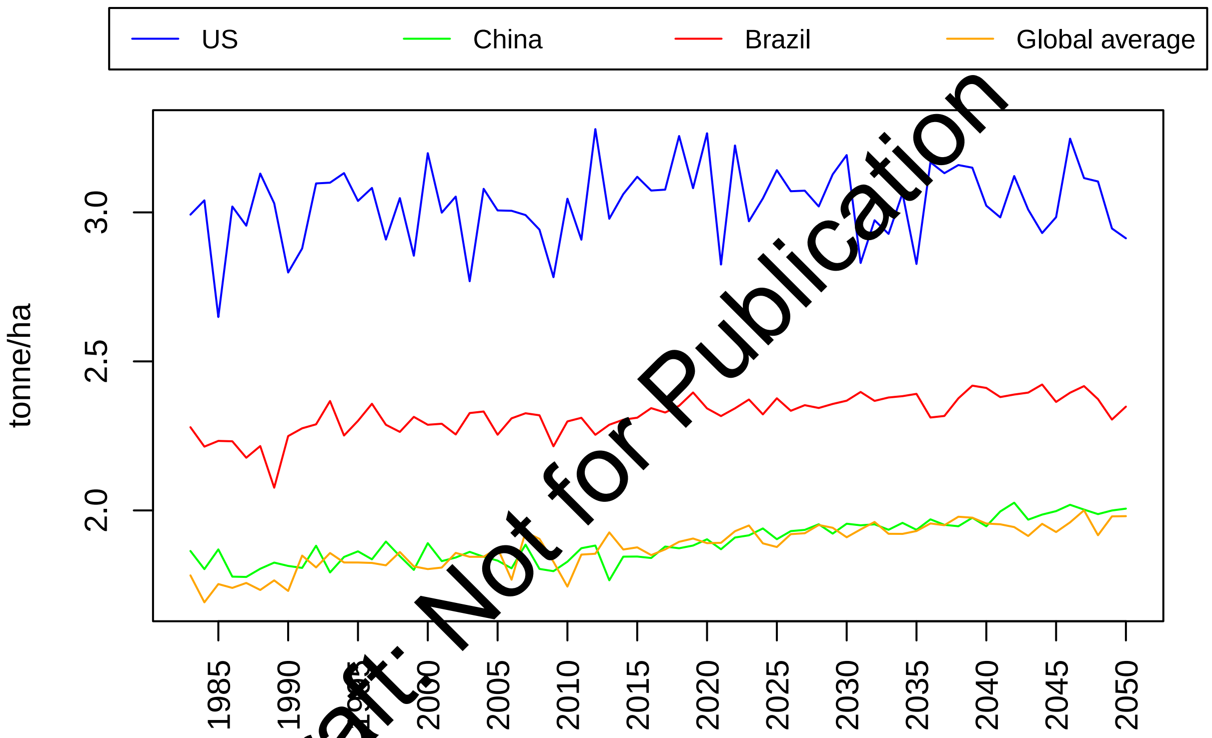


Figure 3: Estimated soybean yields from GGCMI. Source: Jägermeyr et al. (2021). Notes: The estimated yield is the model ensemble mean across the twelve climate models and five crop models.

2.4 Wheat

Figure 4 presents the yield changes for wheat, which are projected to increase. This increase could be because the potential for increasing global wheat yields tends to be higher than that for other crops (Guarin et al. 2022). The data from GGCMI indicates that global wheat yields will increase by 9.5 percent by 2050 relative to 2017. Major global producers of wheat include China (who produced 137.0 Mt in 2021), India (production of 109.6 in 2021), Russia (production of 75.2 Mt), the U.S. (production of 44.8 Mt), and the European Union (whose largest producer is France). The yields for these countries are all projected to increase. India (14.9 percent), China (12.2 percent), and Russia (8.5 percent) are projected to have larger increases than those for France (4.5 percent) and the U.S. (4.1 percent). The numbers for India, Russia, and France are not shown in the figure.

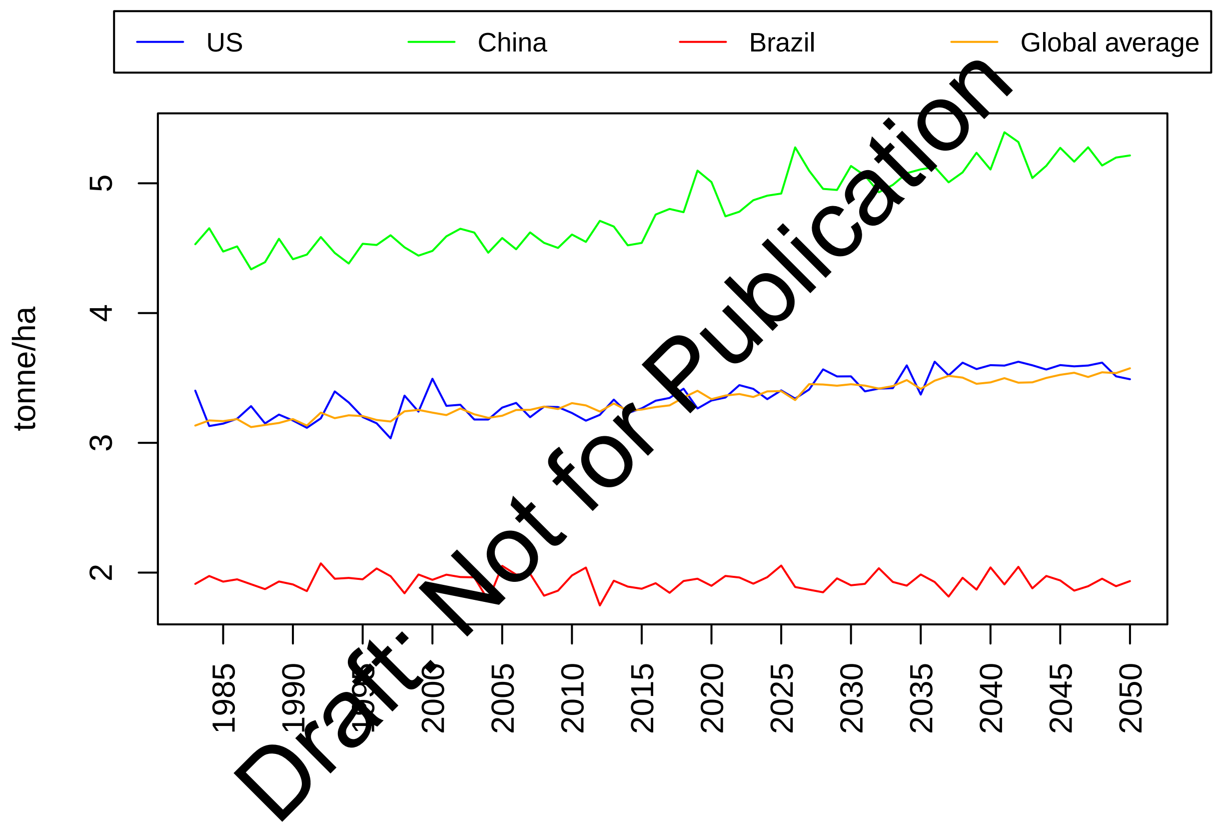


Figure 4: Estimated wheat yields from GGCMI. Source: Jägermeyr et al. (2021). Notes: The estimated yield is the model ensemble mean across the twelve climate models and five crop models.

3 Livestock

Although there has been research on the potential impacts of climate change on livestock systems (P. K. Thornton et al. 2009; Boone et al. 2018; Godde et al. 2020), there is no consortium like the GGCMI that has put together a set of potential impacts. As such, we produce our own estimates to complement the crop yield information. To do so, we use the G-Range model to simulate the impacts of climate change scenarios on mean herbaceous biomass and how such changes affect livestock productivity. G-Range is a global ecosystem model developed to simulate plant functional groups (i.e., herbaceous plants, woody shrubs, and trees) on rangelands. Within G-Range, the relative abundance of herbaceous plants, shrubs, and trees can change relative to one another over time due to changes in the climate. This is important, as not all plant types can be grazed by livestock. For instance, cattle mainly graze on herbaceous plants while goats can consume herbaceous or shrub plants. We simulate changes to herbaceous biomass on global rangelands due to climate change using the same climate scenario as that used by GGCMI in the data we present—SSP 5, RCP 8.5. Similar to the GGCMI work, we use climate data from different GCMs.[4] We present the range of results across these five GCMs as well as the mean. Climate data used includes monthly precipitation, maximum temperature, and minimum temperature. The model is able to estimate potential impacts from CO2 fertilization—where CO2 levels increase and plants respond by increasing productivity and decreasing transpiration depending on C3 and C4 photosynthetic pathways. However, given that CO2 fertilization is not considered in the crop yields, we adopt the same assumption for livestock and consider no CO2 fertilization. We use the herbaceous biomass changes to simulate the impact of climate change on livestock productivity, focusing on milk and meat productivity.

3.1 Rangelands

G-Range is a model that considers rangelands, i.e., grassland production systems.[5] Grassland systems support ruminant species, including large ruminants such as cattle and buffalo, and small ruminants including goats and sheep. Monogastric livestock such as pigs and poultry, by contrast, are more often produced in landless systems (Pandey and Upadhyay, 2022). Even in industrialized countries that have well-developed landless livestock systems, some livestock raising is often performed in grassland systems. For example, cattle production in the United States is split into two production systems: cow-calf production and cattle feeding. Cow-calf production is primarily a grassland system, as beef cattle graze on pasture year-round and are fed little, if any, grain. In the landless feedlot system, by contrast, cows are confined and fed on grain, supplements, silage, and hay (USDA, ERS 2022).

The locations of global rangelands are shown in Figure 5. Rangelands occur on all continents other than Antarctica. The African landscape is dominated by rangelands, particularly the northern half of the continent. Australia is also mostly rangelands, other than along the southeastern and southwestern coasts. South America has rangelands along the western coast and throughout the central and eastern parts as well, and a smaller portion of the north. In North America, rangelands cover much of the western half of the United States and Mexico, northern Canada and Alaska. Rangelands are the primary landscape in Central Asia, and cover much of Eastern Asia except for the coastal regions. The western part of South Asia and the Middle East are also mostly rangeland regions. Southeast Asia, Central America, and Europe are mainly covered in other landscape types and are not major rangeland regions.

The distribution of cattle on rangelands is shown in Figure 6. The areas of rangelands that have the highest concentration of cattle are in the Sahelian region of Africa which stretches across the continent, and parts of South America and North America. Central Asia and most of Australia are also areas of rangelands stocked with large concentrations of cattle. Additional areas of greater concentration are scattered throughout other rangeland areas, though in general far northern latitudes and areas dominated by deserts such as the Saharan region of Africa, do not hold large concentrations of cattle.

[4]Following Boone et al. (2018), we use 5 GCMS. They are CSIRO-Mk3.6.0 (Collier et al. 2011); GFDL-CM3 (Donner et al. 2011); GISS-E2-R (Schmidt et al. 2006); HadGEM2.ES (Collins et al. 2011); and MIR-CGCM3 (Yukimoto et al. 2012).

[5]It could be argued that feedlot production would be more impacted by crop yield changes since those animals depend on crops versus land for food.

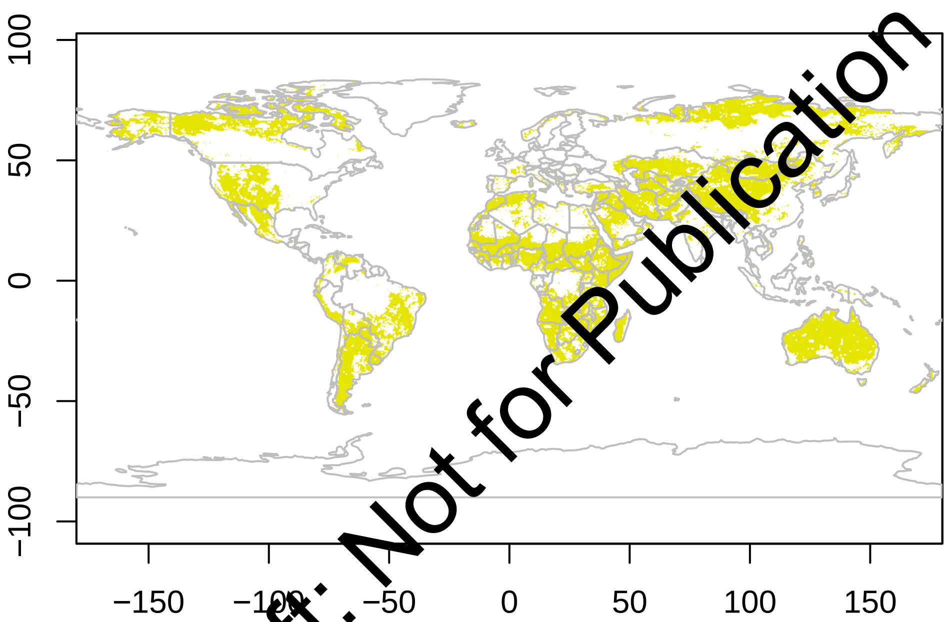


Figure 5: Rangelands (shown in yellow) Around the World. Source: G-Range. Note: The G-Range program identifies 15 different biomes as rangelands. Each biome has different modeling parameters. This figure identifies these 15 rangeland biomes in yellow. Land that is not identified as rangeland is shown in white and is not modeled by G-Range.

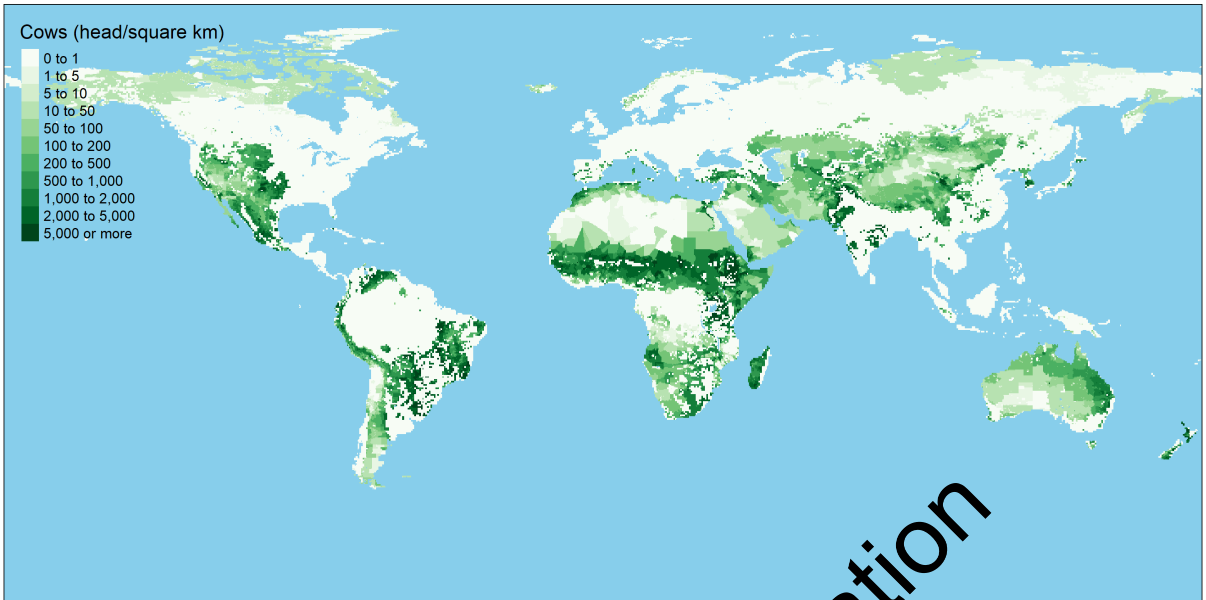


Figure 6: Distribution of Cattle on Rangelands. Source: Livestock distributions come from the Gridded Livestock of the World (GLW) 2015 while area delineations of rangelands come from G-Range

3.2 Calculating Meat and Milk Productivity

G-Range models the globe as 0.5 degree (approximately 50 km2) square grid cells covering all rangelands on Earth (Boone et al. 2018). Each cell is made up of four parts that sum to 1: bare cover, herbaceous plants, shrubs, and trees. Each cell also includes several other traits such as soil moisture and C/N/P properties. Projected climate data, specifically monthly precipitation and maximum and minimum temperatures can be input into G-Range to simulate each grid cell under different climate scenarios in the future. Nutrient cycling, plant growth, plant death, grazing, fire, and fertilization are simulated for each grid cell by month. Model output, including total above ground biomass and the percentage of each cell made up of herbaceous plants, shrubs, and trees, can be compared between different years to assess the impacts of climate change on availability of grassland forage for livestock.

G-Range provides simulation results for biomass and plant type, but it does not directly simulate animal productivity. We use G-Range results to calculate global and regional changes to animal productivity (both meat and milk) due to biomass changes, following Kwon et al. (2016). While they estimate grass biomass loss using Normalized Difference Vegetation Index (NDVI) data, we use our estimates derived from the G-Range analysis using the following equations.

First, dry matter intake (DMI) is calculated:

$$\mathrm{DMI}_t = \mathrm{biom}_t \gamma \kappa \tag{1}$$

Here, DMI_t is dry matter intake in tons in year t in pixel i, and biom_t is the total grass, or herbaceous, biomass production in year t, simulated by G-Range. This is averaged over the twelve months of each calendar year. γ is the contribution of grass to total feed intake; and κ is the share of above ground grass biomass consumed by livestock. DMI is then used to calculate the total change in meat production, P in pixel i:

$$P = \sum_{i=1}^{I} \left(DMI_{t=2017} - DMI_{t=2050}\right) \theta_m x_t \tau_t \tag{2}$$

Here, θ_m is the conversion factor of grass DMI to the fresh weight of meat, which comes from Wirsenius, Azar, and Berndes (2010). These vary based on region and production system. X_t is the number of livestock (measured in tropical livestock units, or TLU) in pixel i which comes from the 2015 Gridded Livestock of the World dataset. Finally, τ_t is the off-take rate which equals the number of animals marketed as a percentage of total animals kept. This analysis ignores any weight loss that might occur to animals that are kept alive and not sold. Milk productivity is calculated in the same way, except that θ_m is the conversion factor of grass DMI to the fresh weight of milk, there is no off-take rate in the equation, and X_t measures the number of milking cows in pixel i.

3.3 Results

3.3.1 Herbaceous Biomass Results

Between 2017 and 2050, it is estimated that the world's rangelands will lose approximately two percent of their herbaceous biomass—assuming no CO2 fertilization and no human intervention. These numbers are illustrated in figure 7. The global range is as low as -6 percent and just above 0 percent across GCMs. Regionally, changes to herbaceous biomass vary much significantly. The following regions are estimated to gain herbaceous biomass: Caribbean, North America, Eastern Europe, Northern Europe, Western Europe, Central Asia, Eastern Asia, Southern Asia, Western Asia, and Melanesia. The largest percentage increases are predicted for Northern Europe, Eastern Europe, and Northern America. Because Northern America has more herbaceous biomass than these other regions, Northern America is predicted to have the largest total increase in herbaceous biomass. The regions with the greatest herbaceous biomass losses in percentage terms are mostly in Africa; each African region is projected to lose herbaceous biomass.

3.3.2 Meat and Milk Productivity Results

Regional and global meat and milk productivity results vary from herbaceous biomass results because of the additional factors used in calculating productivity included in equations 1 and 2. In general, the sign of results matches those of herbaceous biomass: regions that will lose herbaceous biomass are expected to see reductions in meat and milk yields as well. West Africa, which is predicted to have the greatest decline in herbaceous biomass at -34 percent, is also predicted to have the greatest declines in meat and milk yields, each at -36 percent (see, figure 7). Regions with predicted gains to herbaceous biomass are also generally expected to have increases in meat and milk yields, but these are greatly attenuated in some regions. For instance, herbaceous biomass is predicted to increase 22 percent in Northern America, but meat and milk yields will remain almost constant; increasing by only about 1 percent each. This is likely because livestock in Northern America obtain most of their food from different sources, so the gain in herbaceous biomass does not necessarily translate into large changes in meat or milk yields. In general, climate change improves agricultural suitability of the temperate regions (Schneider, Zabel, and Mauser 2022)—leading to gain in herbaceous biomass and corresponding meat and milk productivity in Northern America and Europe.

Figure 7 summarizes results discussed in this section, i.e., the percentage change of herbaceous biomass and the corresponding meat and milk productivity change from 2017 to 2050. The figure shows the pattern of regions which gain and those which lose due to climate change.

4 Shifting AEZs

AEZs are a way of classifying land data based on biophysical characteristics of the land itself as well as the climate. Globally, there are 18 AEZs. AEZ categories are created using information on length of growing period (LGP) and thermal climate based on latest information from IIASA/FAO GAEZ v.4 (2023). The LPG shows the number of days in a year when the prevailing temperature and available moisture permit crop growth (i.e., days wherein average daily temperature is above 5°C and actual evapotranspiration is above the threshold level of 0.5). These are grouped into six categories, as shown in Table 7. On the other hand, the thermal climates broadly classify each grid-cell according to tropics, subtropics, temperate, boreal and arctic climates. The original thermal climates (8 types) are reclassified to 3 zones (Tropical, Temperate and Boreal). These two pieces of information, combined with the moisture regime, leads to 18 distinct AEZs (Table 1).

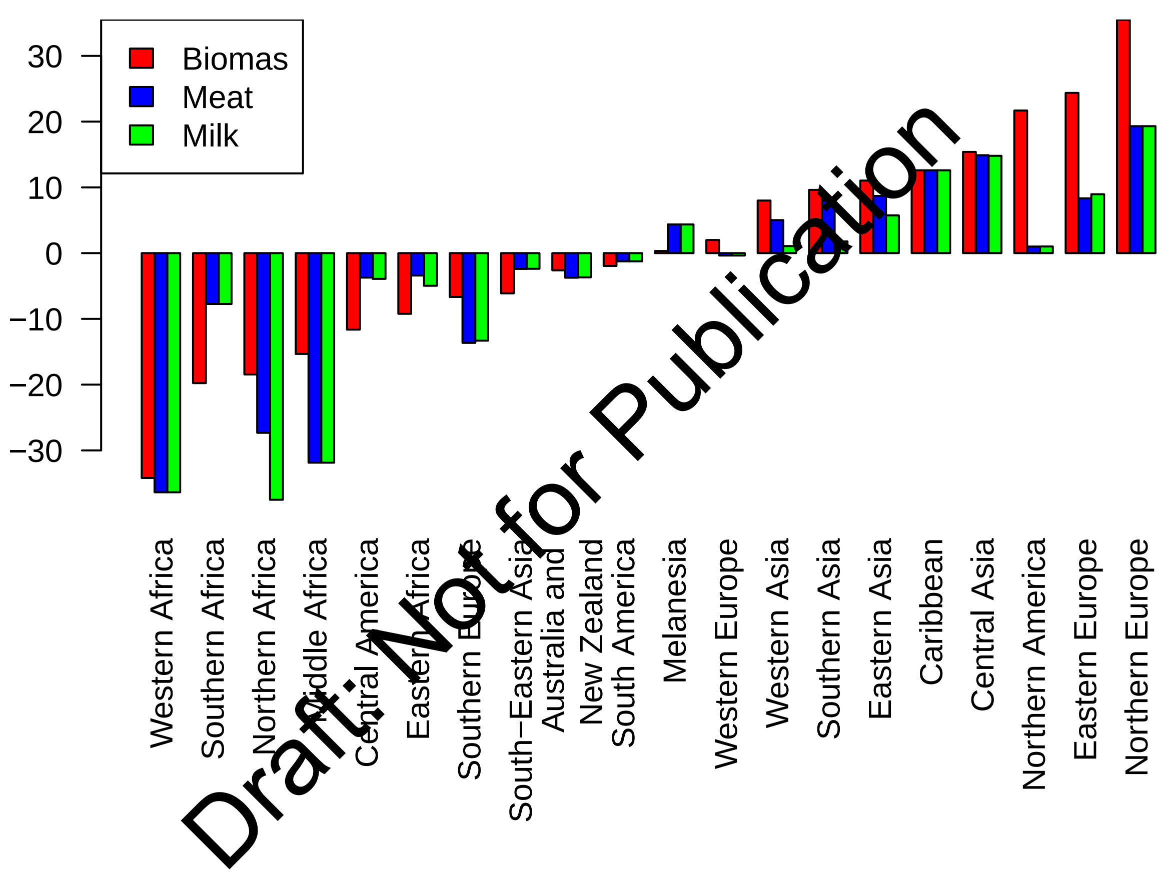


Figure 7: Percentage change from 2017 to 2050 by region (averaged across GCMs)

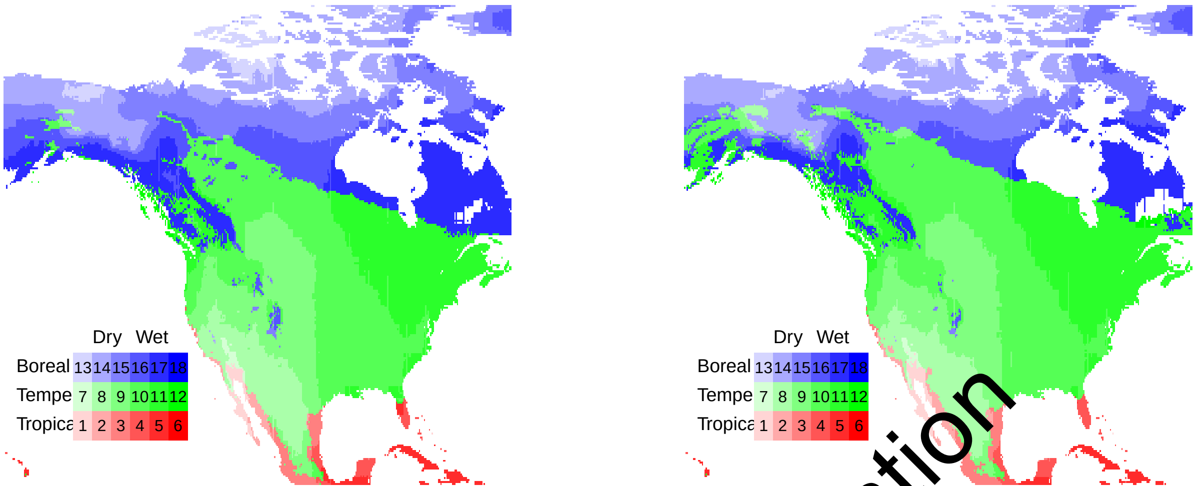
Table 1: GAEZ classification in GTAP for the AEZ database

Length of growing period in days	Moisture regime	Climate zone	GTAP class
0-59	Arid	Tropical	AEZ1
		Temperate	AEZ7
		Boreal	AEZ13
60-119	Dry semi-arid	Tropical	AEZ2
		Temperate	AEZ8
		Boreal	AEZ14
120-179	Moist semi-arid	Tropical	AEZ3
		Temperate	AEZ9
		Boreal	AEZ15
180-239	Sub-humid	Tropical	AEZ4
		Temperate	AEZ10
		Boreal	AEZ16
240-299	Humid;	Tropical	AEZ5
		Temperate	AEZ11
		Boreal	AEZ17
>300 days	Humid; year-round growing season	Tropical	AEZ6
		Temperate	AEZ12
		Boreal	AEZ18

The Global Trade Analysis Project (GTAP) database uses AEZs to classify land types. The AEZ data from GTAP is used frequently by those modelers who are using a CGE framework, even if they do not use the GTAP model itself. This is because the data from GTAP (both the standard set of economic data, as well as the AEZ) is the only real comprehensive set of data that can be used by global CGE models. The GTAP model maps these regions in 5-minute grid-cells (approximately 21 square km) onto maps of land cover, land use, and administrative boundaries. The GTAP AEZ data began in the GTAP version 6 database (which was set to 2001). Since then, the GTAP data has been updated, and the system to bring AEZ data in has been refined. That is, starting with GTAP version 9 (set to 2011), the land use and land cover data was created directly from the latest, high-resolution (i.e., 5-minute) spatial land cover and land use maps in combination with national-level statistics (Baldos et al. 2017). To create the database, first GTAP takes administrative boundaries from the Global Administrative Areas map v2.8 (2016) which contains information on the boundaries of 256 countries. These are mapped to the GTAP regions. Each 5-minute grid-cell (approximately 21 square kilometers) of the Earth's land area is classified according to the AEZ. As the climate changes over time, so do the AEZs. For instance, areas may become more or less arid over time, or move from temperate to tropical climate, thus experiencing a shift in their AEZ. We show what has happened across the AEZs, using the United States as an example. Figure 8 illustrates these changes between 2017 and 2050. For a simple illustration of the changes, note the expansion of the tropical AEZs in Florida, the reduction of boreal AEZs in the Rockies, and a dramatic expansion of temperate AEZs in Alaska.

One additional piece of evidence regarding the shift in AEZs over time, using the U.S. as an example is Table 2—which shows the number of counties in the U.S. and how they changed. AEZs 1–3 and 16–18 are not in the U.S.—these AEZs are generally thought of as desert and tundra areas. The U.S. did have one county in AEZ 4, although it shifted to another AEZ in GAEZ v. 4. The U.S. did not have any land in AEZ 6 in GAEZ v. 3, but four counties exhibited those growing conditions in GAEZ v. 4. The U.S. had very little land in these AEZs, as well as AEZs 13, 14, and 15. To provide some context into the changes for the other AEZs, Table A.2 also has crop yields (using 2014 as an example).[6] The U.S. has most land in AEZs 7–12, which are all temperate climates (Table 2). First, notice that land moved out of AEZs 7—10, into AEZs 11

[6] Of course, the number of counties is not a direct indicator of how much land is in an AEZ, but rather it is a proxy. We acknowledge that the land size could be different but constructing a measure of land size plus yields would be computationally difficult.



(a) 2017 (b) 2050

Figure 8: Changes in AEZs in North America from 2017 to 2050

and 12. That is, they moved out of less moisture conditions into more—with more growing days—making them more suitable for agriculture. The results are consistent with Schneider, Zabel, and Mauser (2022) who estimated that the share of land in North America, which changed from marginally suitable land to suitable arable land increased from 31 percent to 38 percent. However, Table A.3 also indicates that the highest crop yield in 2014 was for AEZ 9—which is moist semi-arid, with 120–179 growing degree days. The second highest yield for an AEZ is in AEZ 7, which has the least amount of moisture. However, this AEZ includes Imperial and Riverside counties in California, which had the 14th and 43rd highest farm related income in 2017 (USDA, 2017).

Table 2: The number of counties in the U.S. by AEZ across time

AEZ	2017	2050	Crop Yields for 2014
1	0	0	0
2	0	0	0
3	0	0	0
4	1	0	0*
5	2	2	0*
6	0	4	0#
7	124	96	6.89
8	581	323	5.66
9	212	177	8.57
10	835	649	7.54
11	749	1053	6.13
12	559	787	6.69
13	2	1	0*
14	12	5	0*
15	2	1	0*

AEZ	2017	2050	Crop Yields for 2014
16	0	0	0
17	0	0	0
18	0	0	0
NA	30	11	NA
Total	3109	3109	6.92

4.1 Approach to Shifting AEZs

To estimate shifts in AEZs, we rely on NEX-GDDP that produces daily weather forecasts that expand up to the year of 2100 at a fine spatial resolution of 0.25 degrees (about 25 square kilometers). NEX-GDDP has a total of 21 climate models, and in our study, we employ all available models to add some level of variability to our results and additional robustness checks. We expect that using a single year for our scenarios can introduce weather shocks that are unique to a single year and drive our results (Burke and Emerick 2016). In this study, we are interested in changes in climate as opposed to changes in weather since we are interested in overall changes to agricultural production rather than outliers that may occur because of extreme weather events. Therefore, we minimize the role of single-year weather shocks by averaging each year by the five years surrounded such year. For instance, data for 2017 is calculated by averaging data from 2015–2019 while data for 2050 is calculated by averaging data from 2048–2052.

As described in the previous section (e.g., Table 1), shifts in AEZs require the calculation of growing degree days and the level of moisture in each region. To calculate growing degree days, we exploit the temporal granularity of NEX-GDDP to calculate the amount of degree days per day during our periods of interest (2017 and 2050). We follow the work of Beckman, Marcos Ivanic, and Nava (2023) for the calculation of growing degree days and set the threshold at 300 C. In addition, we exploit the granular spatial resolution of NEX-GDDP to calculate the changes in the world's the moisture zones (Figure 9) and climate zones (Figure 10). Each figure shows the original state of the moisture and temperature land types in 2017 and the projected changes to 2050. These gridded projections are then combined to produce the global shifts in AEZs (Figure 11 and 11).

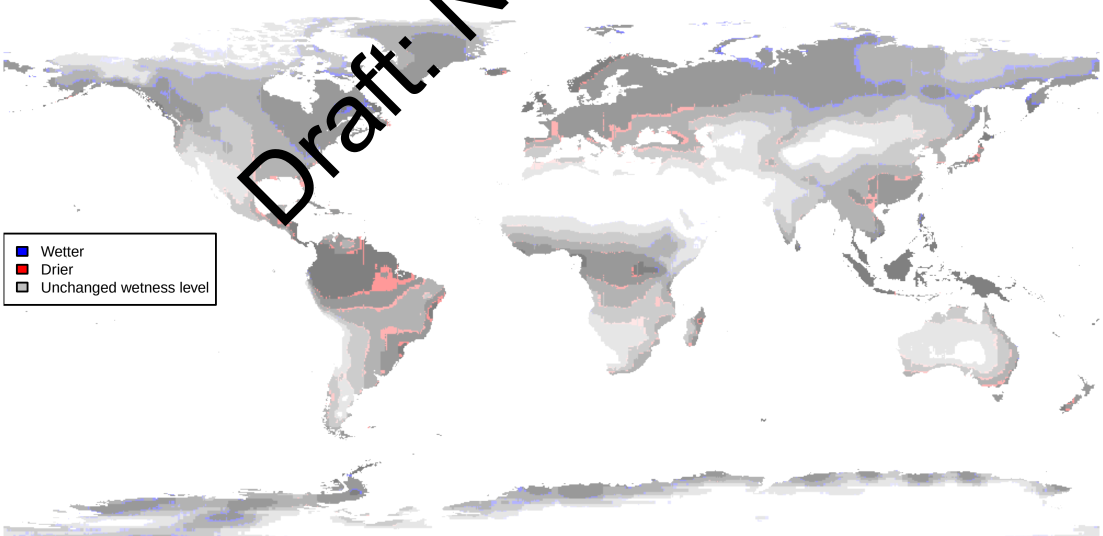


Figure 9: Changes in moisture zones from 2017 to 2050

Figure 9 illustrates the changes in moisture zones from 2017 to 2050. The first insight is that moisture zones

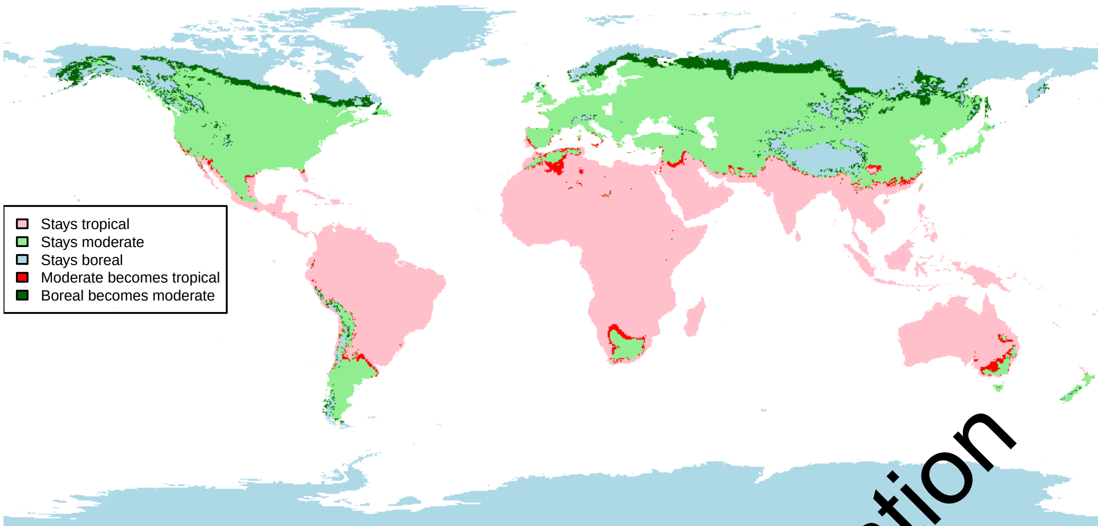


Figure 10: Changes in temperature zones from 2017 to 2050

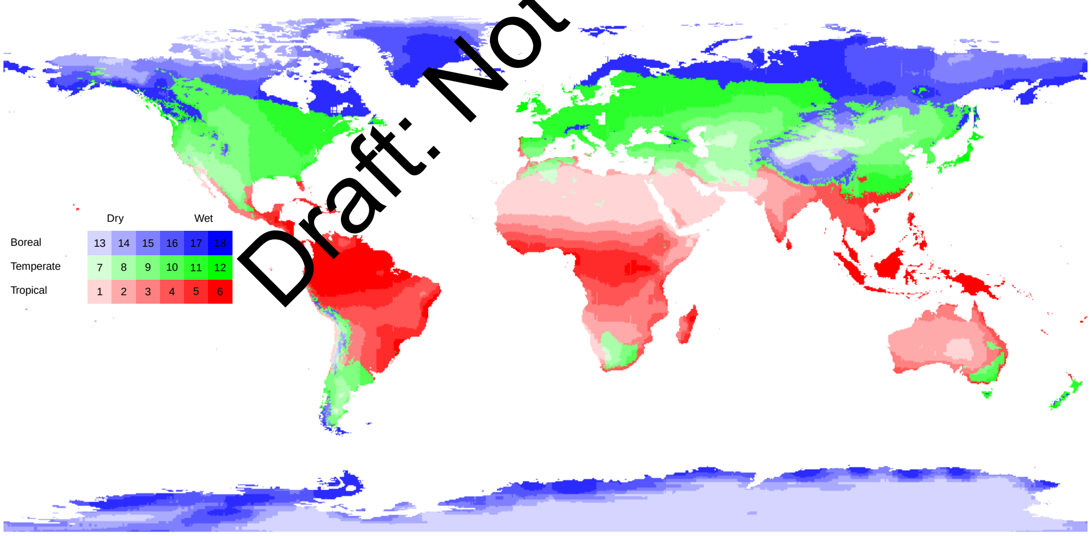


Figure 11: AEZs in 2017

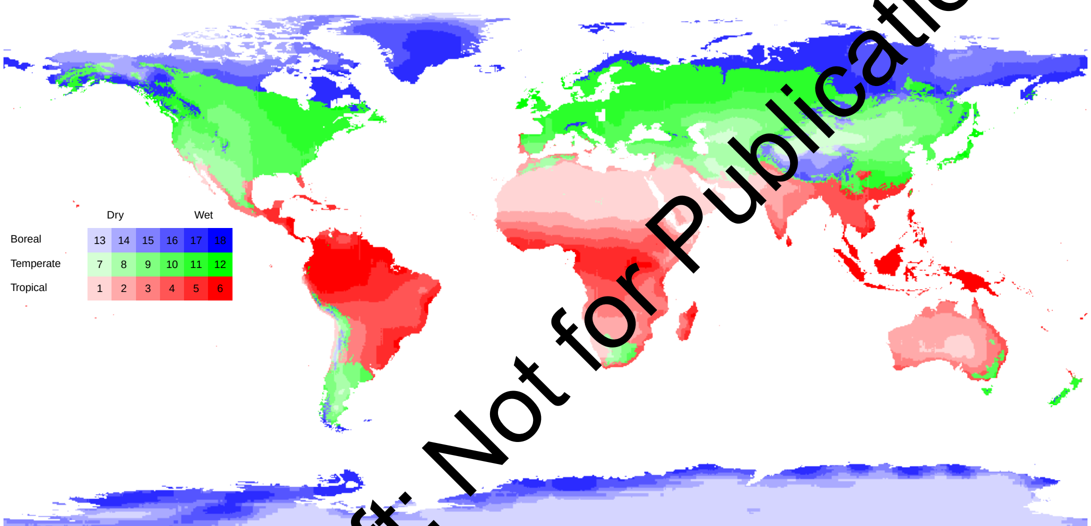


Figure 12: AEZs in 2050

are not expected to change significantly in the next three decades. The figure shows the zones that are predicted to stay the same in the shades of gray, with the darkness of the shading representing the level of wetness. The areas that switch their moisture category are shown in the shades of red (for the areas that are predicted to become drier) or in blue (those becoming wetter). Some of the largest areas that switch their moisture category are in South America (getting drier), and in Northeast Canada and East Russia (both getting wetter).

Most of the shifts in AEZs are predicted to be driven by increases in temperature rather than moisture. Figure 10 illustrates how large swaths of temperate zones expand farther North into the boreal zones (in dark green). Similarly, we observe that tropical zones expand into the temperate zones (dark red). In fact, several studies already show that most of the changes in agricultural production due to climate change are driven by raises in temperature rather than changes in precipitation Beckman, Maros Ivanic, and Nava (2023).

Using NASA's daily global forecasts for 2050 that provides changes by moisture zones (Figure 9) and climate zones (Figure 10), and following the method of Ramankutty and Foley (1999), we then re-categorize each global AEZ as either tropical (the lowest temperature never falls below 0°C), temperate (the lowest temperature never falls below -45°C and temperature adjusted growing degree days $\leq$ 1,200 °C.days for days with average temperature $\geq$ 5 °C) and boreal for the rest. Using this procedure, we obtain forecasted changes in each AEZ in each country between 2017 and 2050, which are described in figure 11.

5 How Could Climate Change Impact Food Prices and Food Security?

CGE models are often used to evaluate the potential impacts of a policy, as they provide economywide and commodity-specific effects while considering inter-industry linkages. A particular benefit of CGE models for this paper is that resources (land, labor, and capital) that can be used for agricultural and manufacturing production are finite—so the model tracks inter-industry and global linkages. The model (and data) we use are from GTAP—these resources, especially the data are the main resources used by CGE modelers. The model itself has been used in many recent policy analyses, including estimating the impacts of the EU's Farm to Fork policy (Beckman et al. 2020).

With the inputs in hand (changes in yield and livestock productivity, and shifting AEZs), the next step is to use a CGE model to provide estimates of how climate change could impact food prices and food security. Of particular concern is the potential larger negative effects of climate change on agricultural production in Africa as shown earlier, and yet it is a continent that already experiences some of the highest incidences of poverty and food insecurity. We employ the GTAP-AEZ framework (the model and database that explicitly accounts for land as mentioned earlier in the shifting AEZ section). To give an idea on how the agriculture sector might look in 2050, we also need information on how demand might change. To do so, we include Gross Domestic Product (GDP) and population growth scenarios from CEPII (Fontagné, Perego, and Santoni 2022) as our baseline. In the baseline, we assume that population increases by 11.1 percent and GDP increases by 141.7 percent from 2017 to 2050. Population is exogenous in our model, but GDP is endogenous. To force the model to reproduce the projected growth in GDP, we swap it with productivity—i.e., productivity will change to meet the change in GDP. Given that there are estimates on past changes in agricultural productivity,[7] we apply the productivity shock from GDP to non-agricultural sectors. We talk more about that assumption later. There are many regions and sectors in the model. We aggregate them to a reasonable amount. The aggregation is in A.4 for regions and Appendix A.5 for sectors.

5.1 Changes to Production

We first present results for changes to global production across the different inputs (Table 3). We begin with the baseline as that is what largely drives the result for all inputs. Table 3 indicates that production

[7] Morgan et al. (2022) estimate past total factor productivity (TFP) for agriculture for every country. They note that TFP in agriculture has slowed in past years. For our work here, we apply the lowest cumulative growth over a 30-year period observed in the historical data to try to keep the TFP values as a lower bound.

Table 3: Percent change in global production

Sector	Baseline	Crop Yields	Livestock productivity	Land shifts	Total
Rice	38.9	-0.7	0.0	1.3	39.4
Wheat	31.4	-0.3	0.5	1.0	32.1
Coarse grains	43.1	-1.2	-0.4	2.6	44.5
Fruits/vegetables/nuts	44.8	-1.3	-0.4	2.0	45.5
Oilseeds	37.7	0.0	-0.2	2.2	39.9
Sugar crops	15.9	0.1	-0.1	1.3	17.3
Plant-based fibers	28.3	1.4	1.7	0.3	30.0
Other crops	32.8	0.0	0.2	0.9	33.8
Meat/livestock	62.3	-2.5	-2.2	1.3	61.1
Extraction	-13.5	-0.3	-0.3	0.2	-13.6
Processed food	61.2	0.2	0.2	1.0	62.5
Manufacturing	50.3	-0.1	-0.1	0.1	50.3
Services	109.8	0.0	0.0	0.0	109.8

increases by double digits for all sectors (except a 109.8-percent increase in services). This is because the large increases in GDP from CEPII requite large increases in productivity—which increase production. The estimates for changes in productivity are presented in Table 4. For agriculture, note that several regions had negative changes in TFP in the past. But these tend to be regions that are on the smaller end of global production. The major agricultural producers (East Asia, North America, USA, South America, and the EU) all have had increases in TFP. For non-agricultural sectors, there are some big increases in productivity. The rest of the world (which is essentially some very small islands not accounted for in the bigger regional grouping) is the only region with a decrease in productivity. All other regions have increases—after the EU increase of 38.2 percent, all other regions have an increase greater than 50 percent. And several regions have triple-digit increases or even increases in the thousands. These changes are what lead to the large increase in global production in the baseline.

Results by region are presented in Table 5, where every region (except for the rest of the world) has an increase in its total production. This ranges from 67.8 percent for East Europe (recall that they have the lowest gains in both agricultural and non-agricultural productivity, other than the rest of the world) to 865.4 percent for South Asia. This is also the region with the largest gains in non-agricultural productivity—thus the changes in production are highly tied to the changes in productivity. Note that there are also several regions that have a decrease in agricultural production in Table 6—all of which are those with negative agricultural productivity growth (Table 4). The regions with the negative agricultural productivity growth and subsequent decreases in agricultural productivity tend to be those who are smaller producers who depend on the world for imports—possibly negatively impacting their food security. These include all of Africa's sub-regions except southern, and to a lesser degree, northern Africa.

Table 4: Productivity assumed from the baseline (percent change)

Region	Baseline GDP change	Non-agricultural productivity	Agricultural productivity
Oceania	166.2	86.9	18.2
East Asia	287.1	117.6	33.4
Southeast Asia	314.7	165.1	44.8
South Asia	860.8	719.4	31.9
USA	128.3	67.5	22.5
Rest of North America	131.9	73.5	17.8
South America	99.1	54.8	24.5
Central America	259.0	189.5	4.4
Caribbean	119.1	76.6	-22.4
EU	84.7	38.2	29.7
Rest of EFTA	129.5	63.3	13.2
East Europe	68.9	58.9	-15.1
Rest of Europe	132.5	71.8	0.0
Rest of Soviet Union	355.5	308.7	-19.0
Western Asia	129.0	111.3	-15.1
Northern Africa	207.9	151.8	-0.6
Western Africa	640.9	2640.4	-0.3
Central Africa	141.6	161.5	-20.5
South Central Africa	292.3	439.1	-19.2
Eastern Africa	646.7	1846.6	-6.8
Southern Africa	117.5	67.7	7.7
ROW	-0.1	-1.0	0.0

Region	Baseline	Crop Yields	Livestock productivity	Land shifts	Total
Oceania	165.9	0.2	-0.4	0.1	166.2
East Asia	285.1	1.8	0.9	0.2	287.1
Southeast Asia	314.9	-0.3	-0.2	0.1	314.7
South Asia	865.4	-5.8	-0.3	1.2	860.8
USA	128.4	-0.1	0.0	0.1	128.3
Rest of North America	132.4	-0.5	-0.3	0.0	131.9
South America	99.0	-0.0	-0.3	0.2	99.1
Central America	256.1	2.6	2.3	0.2	259.0
Caribbean	118.2	0.8	0.6	0.1	119.1
EU	84.5	0.1	-0.0	0.1	84.7
Rest of EFTA	128.0	1.5	1.3	0.1	129.5
East Europe	67.8	1.0	0.9	0.1	68.9
Rest of Europe	131.0	1.3	1.5	0.2	132.5
Rest of Soviet Union	353.6	1.7	2.5	0.1	355.5
Western Asia	129.4	-0.5	0.5	0.1	129.0
Northern Africa	207.3	-1.2	-0.8	1.9	207.9
Western Africa	661.7	-21.8	-19.9	1.0	640.9
Central Africa	151.4	-9.9	-6.8	0.1	141.6
South Central Africa	299.9	-8.2	-0.2	0.6	292.3
Eastern Africa	632.1	1.8	-2.2	12.8	646.7
Southern Africa	117.5	-0.2	-1.0	0.2	117.5
ROW	-0.1	-0.0	-0.0	-0.0	-0.1

Table 5: Change in total output by region

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	198.8	65.5	41.1	208.5	99.4	45.8	16.0	19.3	82.9	-9.8	51.0	-55.4	91.1
East Asia	71.7	47.7	24.4	39.5	56.7	7.3	24.4	84.6	141.0	39.4	58.6	72.3	124.6
Southeast Asia	68.9	207.5	53.2	48.2	58.3	31.5	57.0	30.8	80.3	15.2	158.2	51.7	186.9
South Asia	24.7	-0.7	80.7	53.5	35.4	50.2	33.8	-6.0	54.2	-13.3	93.8	1316.1	567.5
USA	183.3	43.3	61.3	82.4	22.6	27.0	25.0	-7.3	100.8	-30.8	55.3	-43.8	81.4
Rest of North America	40.5	193.5	12.0	52.5	93.2	[illegible]	26.9	-14.9	32.2	-29.9	35.7	-53.4	91.8
South America	33.3	33.2	43.7	42.3	30.1	-24.2	37.4	-2.5	44.7	-30.9	30.7	-70.9	75.5
Central America	41.8	140.6	15.0	42.5	9.8	17.3	35.8	-22.2	42.7	2.4	23.5	123.8	185.3
Caribbean	11.9	-10.1	0.7	-11.3	-35.4	38.5	-30.4	-50.9	-22.7	-72.0	-25.1	-64.2	102.1
EU	357.7	64.2	74.9	77.2	85.8	77.9	115.0	108.8	165.9	28.4	120.8	-78.3	51.2
Rest of EFTA	2146.0	42.5	29.4	45.8	60.0	30.5	419.6	26.2	64.2	-21.9	49.4	-67.8	79.7
East Europe	75.7	10.0	31.6	47.3	22.9	23.8	69.7	41.7	15.3	-25.1	11.3	-37.4	64.9
Rest of Europe	88.1	30.9	9.7	[illegible]	1.7	-10.9	28.9	-13.6	-0.8	-30.6	-25.3	-66.0	92.4
Rest of Soviet Union	43.2	-11.1	10.0	12.6	-18.0	1.4	11.9	-47.0	-5.0	-47.9	-11.1	346.5	315.4
Western Asia	49.4	-7.4	14.0	21.4	7.0	20.4	40.4	3.8	3.5	-27.1	4.0	-10.3	145.1
Northern Africa	48.9	7.4	[illegible]	24.5	13.0	19.6	70.5	40.4	19.2	-21.1	22.3	63.3	165.5
Western Africa	-16.5	[illegible]	60.5	46.6	3.3	22.7	34.4	-65.8	8.3	-59.7	-70.1	6466.6	1765.9
Central Africa	19.1	-3.4	-42.8	-33.6	23.0	-6.7	-0.0	8.8	-21.4	-72.6	-14.1	14.1	214.8
South Central Africa	-27.8	-36.4	4.6	25.6	19.9	60.2	49.1	-33.7	-47.5	-47.9	-9.9	1238.7	331.6
Eastern Africa	-54.9	-92.0	40.8	53.9	46.5	-4.2	44.6	-70.6	-45.2	-95.5	-48.3	6413.7	1124.4
Southern Africa	128.3	21.3	79.3	59.5	79.9	61.0	97.1	-31.1	123.2	-10.1	100.7	-69.5	83.1
ROW	242.0	665.6	248.9	239.9	389.2	36.6	451.7	157.2	62.7	-7.0	13.9	-97.2	5.6

Table 6: Change in output in baseline (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	7.4	-21.8	23.7	40.2	65.7	1.3	11.4	-7.2	-18.4	1.0	-0.3	0.9	0.2
East Asia	3.8	11.5	4.3	7.6	11.1	-0.4	10.8	21.3	24.3	-0.7	2.5	-2.0	0.3
Southeast Asia	2.2	-82.6	-2.3	-4.3	4.6	5.4	-9.6	-9.3	-1.8	-0.5	4.6	-0.8	-0.1
South Asia	-3.8	-6.9	-5.3	-7.5	-0.4	-2.5	-7.2	-10.9	-4.1	0.2	-2.5	9.1	-1.2
USA	-9.9	11.4	-10.9	-0.8	-14.8	-0.6	0.7	-6.8	-3.0	0.1	-0.7	0.3	0.0
Rest of North America	-0.8	-32.0	-1.8	-6.5	17.9	-2.0	-5.5	-13.4	-8.1	1.3	-1.5	1.3	-0.2
South America	-0.5	-15.2	10.1	2.2	1.5	0.1	7.5	-0.5	-3.3	0.1	0.2	0.4	-0.0
Central America	9.8	-33.9	4.6	1.6	0.[illegible]	0.2	5.1	-0.5	11.6	-0.2	0.9	-2.1	0.7
Caribbean	1.6	-17.6	0.9	1.5	-1.1	-2.3	5.9	0.1	11.2	-1.5	0.7	-1.0	0.2
EU	-43.2	9.4	2.9	1.7	-8.9	2.8	14.3	1.8	8.1	-0.4	-1.3	-0.5	-0.0
Rest of EFTA	210.5	15.0	14.7	8.3	12.7	3.3	93.9	11.0	141.3	-4.9	1.4	-3.8	-0.4
East Europe	-13.6	5.2	1.8	-0.3	-4.1	-2.2	-0.3	-8.7	11.9	-0.6	-0.7	-0.5	0.1
Rest of Europe	-15.5	6.4	2.1	-2.7	-1.1	-1.6	-3.1	-6.6	13.9	-1.1	-1.6	-2.2	0.4
Rest of Soviet Union	-11.4	5.2	-1.4	-1.7	-12.2	0.5	-7.6	-10.2	8.8	-0.5	3.6	-1.5	0.2
Western Asia	-10.8	-0.7	-8.0	-7.9	-10.4	-2.5	-14.7	-22.2	7.2	-0.1	-0.7	-0.6	0.2
Northern Africa	-2.9	-2.2	-0.2	-4.5	-0.2	-1.3	-4.4	-13.3	-4.2	0.2	-0.4	0.4	-0.1
Western Africa	4.3	-0.2	-4.8	-2.0	-2.1	1.0	10.5	0.8	-46.5	-0.8	0.1	341.7	8.7
Central Africa	1.2	-33.5	-8.0	-7.8	-26.5	-2.6	-3.3	-5.2	-39.9	-8.5	-7.1	5.4	5.2
South Central Africa	-7.8	-24.5	-6.3	-9.2	-7.0	13.4	-13.5	-16.5	-5.1	-1.2	-6.9	15.0	-1.1
Eastern Africa	3.5	-3.9	0.6	2.5	0.3	-0.5	4.9	1.5	-4.6	0.2	0.4	38.0	3.1
Southern Africa	12.3	5.4	7.8	8.4	4.5	3.6	21.8	7.5	-32.4	1.2	3.2	0.8	0.2
ROW	-41.4	-82.0	73.5	-0.9	-47.5	1.4	21.0	-15.4	-3.3	0.3	1.8	0.5	0.3

Table 7: Change in output due to changes in crop yields (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	-9.1	2.1	-0.2	3.4	0.5	-1.2	0.0	2.1	-17.4	2.2	1.4	1.4	0.1
East Asia	-0.6	0.3	0.5	-0.2	-0.5	0.6	-0.9	-0.5	21.9	-0.5	0.6	-1.2	0.1
Southeast Asia	-1.0	0.5	0.1	0.3	-0.0	0.0	0.2	0.6	-2.2	-0.3	0.3	-0.1	0.1
South Asia	0.2	0.4	-0.1	0.1	0.1	0.1	0.2	0.0	-3.3	0.0	0.2	0.8	0.4
USA	-3.0	0.3	0.7	-0.7	-0.7	0.1	-0.4	-0.2	2.5	-0.5	0.1	-0.0	-0.0
Rest of North America	-2.4	1.7	-0.3	0.2	-2.1	-0.3	-0.1	0.3	-8.2	0.5	-0.2	0.8	-0.1
South America	-1.7	1.1	-0.6	0.3	-0.4	0.3	0.5	1.0	-3.7	0.4	0.3	0.5	-0.1
Central America	-4.8	-1.0	0.4	-0.7	-0.2	0.5	-0.5	-0.2	11.0	-0.2	0.7	-1.8	0.6
Caribbean	-4.8	-3.0	-2.4	-0.2	-0.4	0.4	-0.7	-0.3	10.5	-1.2	0.4	-0.8	0.1
EU	-18.7	0.8	2.0	-2.6	-1.5	-0.8	-1.8	-0.5	7.8	-0.3	-1.3	-0.4	-0.1
Rest of EFTA	-274.6	3.8	8.6	-9.8	-12.1	-0.7	-40.1	-5.0	139.8	-4.5	1.6	-3.5	-0.5
East Europe	-4.4	-0.5	0.6	-0.9	-0.6	-0.6	2.5	-1.4	12.3	-0.5	0.0	-0.4	0.1
Rest of Europe	-13.4	-2.3	0.0	-1.3	-0.0	-1.3	-2.7	-1.6	14.0	-1.0	-1.3	-2.3	0.4
Rest of Soviet Union	-1.2	0.5	0.2	0.4	0.1	1.2	-0.2	0.0	9.0	-0.5	4.4	-1.6	0.4
Western Asia	-3.3	0.3	0.6	-0.0	-0.6	0.4	-0.3	0.2	9.8	-0.3	1.4	-0.9	0.3
Northern Africa	-1.2	0.9	1.3	-0.6	-0.4	-0.3	-0.6	-0.1	-3.4	0.1	-0.4	0.1	-0.1
Western Africa	3.4	0.6	-2.4	-1.3	0.5	1.3	10.4	2.3	-46.6	-0.8	0.7	345.2	9.9
Central Africa	0.2	-7.3	-3.7	-3.5	-2.0	-5.3	2.3	8.6	-38.0	-3.9	-3.0	3.5	3.6
South Central Africa	-0.3	0.4	0.0	-0.1	0.0	0.0	-0.0	0.2	-2.6	-0.0	0.1	-0.2	0.1
Eastern Africa	0.0	0.3	-0.3	-0.1	-0.0	-0.1	1.2	0.4	-5.1	0.0	-0.1	32.9	1.5
Southern Africa	4.2	4.6	0.3	0.4	3.3	0.2	3.6	2.7	-31.4	1.7	3.4	1.2	-0.0
ROW	-9.4	23.4	1.3	-3.4	-12.8	1.2	8.1	4.3	-6.4	0.2	1.7	0.2	0.1

Table 8: Change in output due to changes in livestock yields (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	-3.1	24.7	3.2	-7.1	6.4	-0.3	14.9	-4.2	0.2	0.0	0.0	0.8	-0.0
East Asia	5.1	0.3	0.1	0.6	1.0	0.5	-0.2	1.7	0.9	-0.3	0.9	0.1	-0.0
Southeast Asia	-0.1	-16.4	-0.2	-0.3	0.1	0.7	-2.5	-1.9	-0.3	-0.5	1.3	0.5	-0.1
South Asia	0.2	0.4	1.9	1.6	0.7	2.3	-1.5	2.8	0.2	-1.1	2.6	-3.4	0.7
USA	39.9	0.4	0.3	0.2	-0.6	0.6	1.5	6.5	3.8	-0.6	0.4	0.2	-0.0
Rest of North America	20.3	-4.1	-0.5	-0.3	0.9	0.1	16.9	1.2	-0.6	0.1	0.4	0.8	-0.1
South America	1.6	10.1	1.0	0.8	2.4	0.6	-2.0	0.4	2.7	-0.1	0.7	0.5	-0.1
Central America	-2.4	-20.2	0.5	-1.2	-0.4	0.4	-0.1	-1.1	0.1	0.2	0.5	1.2	0.1
Caribbean	1.2	-21.0	-0.5	-0.4	-0.4	0.1	-2.3	-0.8	-0.6	-0.5	0.1	0.2	0.1
EU	11.2	1.9	1.9	0.4	0.1	-0.6	11.5	-0.1	4.0	2.1	0.5	0.1	-0.0
Rest of EFTA	-245.5	0.7	3.2	3.6	3.6	5.3	-4.7	3.7	-1.3	0.0	-0.7	0.2	0.0
East Europe	-0.7	-0.2	-1.2	-1.0	-0.1	2.1	-2.7	-7.7	0.9	-0.1	0.6	1.0	0.0
Rest of Europe	8.0	6.4	0.8	2.2	1.4	0.6	1.7	8.7	0.3	-2.3	-0.2	0.1	0.1
Rest of Soviet Union	-4.3	-2.5	-0.4	-0.3	-2.8	-0.5	-4.1	-4.0	0.3	-0.3	-0.6	3.0	0.2
Western Asia	-1.6	-1.8	0.4	-0.8	-0.7	0.4	-1.0	-1.5	0.8	-0.4	1.2	0.8	0.1
Northern Africa	-7.0	2.0	4.2	6.5	-2.5	0.3	-14.2	-18.6	1.1	19.9	0.8	-6.2	-1.3
Western Africa	-2.2	-1.0	0.5	0.3	-0.5	0.3	-0.1	-1.1	-1.1	-0.1	-0.0	20.4	3.2
Central Africa	-5.9	-10.4	0.5	0.4	-2.3	0.7	-4.9	-6.0	-0.4	0.8	-0.2	0.9	0.1
South Central Africa	-0.8	-4.1	0.0	0.4	-0.1	0.4	0.4	-2.0	-0.4	-0.0	0.4	1.7	0.0
Eastern Africa	12.6	9.5	12.2	16.4	11.3	4.7	9.0	11.1	3.8	2.4	3.7	-72.2	-6.4
Southern Africa	-48.8	14.5	2.5	-2.7	-0.9	1.9	-22.3	1.2	2.0	-0.4	4.1	0.5	-0.1
ROW	-25.6	-78.5	-14.8	-12.8	-22.8	0.8	-51.3	-23.4	3.7	0.4	1.4	0.9	0.2

Table 9: Change in output due to changes in land types (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers
Oceania	-22.2	-7.6	-22.4	-10.0	-16.9	-32.7	-2.4
East Asia	-20.8	-35.5	-45.4	-37.3	-34.3	-45.1	-40.9
Southeast Asia	-8.3	-28.3	-12.0	-11.0	-12.5	-44.7	-27.3
South Asia	89.2	33.6	116.1	119.1	75.0	92.1	[illegible]
USA	-10.9	-8.7	-19.4	-9.4	-18.5	-13.0	-24.2
Rest of North America	-5.9	-9.4	-13.0	11.9	-19.0	[illegible]	-8.5
South America	-12.1	-18.1	-14.2	-14.9	-17.9	[illegible]	-23.0
Central America	-3.6	-20.1	-2.9	-6.2	-9.1	1.2	-13.6
Caribbean	26.0	-2.7	25.2	31.1	[illegible]	112.5	-2.1
EU	-10.7	-7.2	-19.2	-7.3	-24.0	-41.5	-17.4
Rest of EFTA	-13.8	-13.3	-11.1	-6.2	-18.2	-22.5	-5.7
East Europe	-13.6	5.5	-11.5	[illegible]	-6.6	-16.2	-23.7
Rest of Europe	-12.3	-8.5	[illegible]	[illegible]	-3.1	-22.4	-30.6
Rest of Soviet Union	43.1	16.5	7.5	25.2	7.6	6.3	-3.4
Western Asia	3.5	2.5	-3.2	9.2	1.7	-11.1	-23.8
Northern Africa	2.6	-6.6	10.4	13.2	-12.3	-20.9	-23.2
Western Africa	474.8	[illegible]	796.2	735.8	544.4	604.5	534.4
Central Africa	-5.8	[illegible]	-31.8	-33.4	-5.5	13.3	-27.7
South Central Africa	[illegible]	[illegible]	256.6	261.8	239.4	388.6	260.6
Eastern Africa	219.5	79.2	427.3	431.2	414.0	240.2	279.2
Southern Africa	70.1	6.0	71.4	64.0	44.4	-15.9	33.8
ROW	-38.7	-24.0	-35.5	-32.2	-29.2	-39.2	-38.4

Region	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	[illegible]	-39.9	-51.8	-44.2	-73.6	-63.1
East Asia	[illegible]	-51.9	-58.6	-61.0	-84.9	-76.5
Southeast Asia	-25.9	-47.5	-51.8	-49.5	-83.3	-74.9
South Asia	24.7	79.3	-10.4	10.9	-89.9	-82.9
USA	-15.7	-47.2	-54.5	-44.4	-70.0	-53.5
Rest of North America	-18.2	-39.2	-54.1	-40.4	-73.7	-55.2
South America	-20.7	-32.5	-50.6	-33.7	-60.1	-34.7
Central America	-13.8	-23.3	-34.6	-28.1	-82.7	-73.6
Caribbean	1.3	4.2	-38.4	-3.0	-71.0	-63.1
EU	-34.3	-46.5	-53.0	-56.3	-71.0	-55.6
Rest of EFTA	-27.3	-35.6	-54.4	-49.0	-75.2	-62.0
East Europe	-25.3	-26.4	-54.2	-33.5	-77.1	-69.9
Rest of Europe	-21.6	-14.9	-41.9	-24.3	-74.1	-58.7
Rest of Soviet Union	-12.1	20.1	-43.9	-0.1	-86.7	-84.1
Western Asia	-14.6	-19.2	-50.4	-29.4	-82.2	-79.2
Northern Africa	-17.9	-19.0	-49.5	-30.6	-83.7	-78.5
Western Africa	210.5	173.7	101.5	147.2	-92.7	-91.3
Central Africa	-26.7	-27.0	-42.6	-21.3	-84.1	-82.1
South Central Africa	67.6	11.3	-41.5	20.0	-90.4	-86.3
Eastern Africa	150.6	199.6	67.7	161.1	-92.7	-89.5
Southern Africa	22.8	-27.1	-46.4	-32.3	-72.5	-56.8
ROW	-28.4	-40.1	-49.7	-41.4	-57.6	-40.7

Table 10: Change in prices in baseline (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	-7.9	-3.4	-3.2	-3.9	-13.8	-6.6	-6.0	-5.4	1.0	-0.2	-0.6	-0.3	-0.5
East Asia	-4.0	-12.2	1.2	-9.1	-9.0	-11.9	[illegible]	-7.7	-6.5	-0.0	-1.3	0.2	0.4
Southeast Asia	-9.4	5.1	17.8	3.8	-8.7	10.6	1.3	0.2	1.0	-0.0	-1.4	0.1	0.1
South Asia	-0.6	0.5	51.0	25.3	-11.2	27.2	16.1	9.0	-2.3	-0.5	0.7	-0.1	-0.3
USA	-2.7	-6.6	20.7	0.4	-1.3	-0.2	0.3	-1.8	1.2	-0.1	-0.0	-0.1	-0.2
Rest of North America	-5.1	-2.8	16.4	4.1	-7.3	6.3	2.9	-0.3	4.7	-0.2	0.1	-0.2	-0.6
South America	-6.3	-0.1	2.4	-2.8	-5.4	-2.7	-1.8	-3.3	2.0	-0.1	-0.7	-0.2	-0.4
Central America	-8.1	-2.8	10.0	-2.2	-4.2	-3.3	-1.6	-2.9	-12.0	0.2	-0.5	0.2	0.4
Caribbean	-9.6	-3.4	8.7	-3.6	-4.2	-10.1	-1.5	-3.2	-10.4	0.4	-0.3	0.4	0.7
EU	-4.7	-7.7	7.5	-4.3	-2.1	-3.1	-1.4	-3.2	0.9	-0.0	-0.0	0.2	0.3
Rest of EFTA	-7.6	-4.8	11.5	-6.8	-7.8	-7.8	-5.3	-6.2	-15.8	0.3	0.0	0.8	1.7
East Europe	-2.0	-6.5	7.8	1.1	-3.7	0.4	0.2	-0.6	-8.1	0.0	-0.0	0.2	0.4
Rest of Europe	-4.8	-7.6	13.7	0.4	4.9	0.7	0.2	-1.2	-8.8	0.2	1.0	0.5	1.2
Rest of Soviet Union	8.9	-10.0	13.6	8.0	2.3	6.9	3.8	0.1	-18.5	0.1	-2.5	0.1	0.2
Western Asia	-3.8	-7.0	19.7	12.0	1.0	11.4	6.9	3.9	-6.4	-0.1	-0.1	-0.0	0.0
Northern Africa	-5.1	-5.2	12.5	1.9	-4.5	2.6	2.1	-0.1	5.8	-0.1	-0.3	-0.1	-0.1
Western Africa	-54.2	7.4	8.3	-56.7	-32.5	-40.7	-19.1	-17.1	111.6	-4.4	-9.2	-0.3	-0.7
Central Africa	-8.0	7.8	-0.9	-1.3	7.3	7.1	0.5	-1.0	83.2	1.3	1.6	-0.6	-1.0
South Central Africa	4.4	4.3	103.5	51.9	-16.0	149.9	49.5	16.0	4.9	-0.0	5.7	-0.1	-0.4
Eastern Africa	-20.5	-1.9	22.0	-24.1	-19.8	-20.7	-16.2	-11.3	8.0	-0.5	-1.7	-0.0	-0.1
Southern Africa	-11.2	-7.2	3.3	-9.6	-9.7	-7.0	-5.4	-6.9	4.9	-0.2	-1.4	-0.5	-0.9
ROW	-1.9	-3.0	1.1	-1.0	-2.4	-0.7	-0.5	-1.9	-0.9	-0.1	-0.8	-0.4	-0.7

Table 11: Change in prices due to changes in crop yields (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	-1.6	-0.4	-0.9	-0.8	-0.7	-1.1	-0.9	-0.5	0.9	-0.3	-0.6	-0.5	-0.9
East Asia	-0.1	0.3	0.4	0.2	0.1	0.4	-0.0	0.1	-6.0	-0.0	0.0	0.1	0.2
Southeast Asia	-1.1	-0.1	-0.6	-0.5	-0.6	-0.5	-0.3	-0.2	1.1	-0.1	-0.2	0.0	0.0
South Asia	-0.5	-0.1	-1.1	-0.7	-0.6	-0.6	-0.5	-0.4	-1.8	-0.1	-0.3	-0.0	-0.0
USA	-0.3	0.0	0.1	-0.2	-0.2	-0.0	-0.1	-0.1	0.0	0.0	0.1	0.0	0.1
Rest of North America	-1.0	0.0	-0.5	-0.4	-0.6	-0.6	-0.3	-0.3	4.5	-0.1	-0.1	-0.1	-0.3
South America	-1.0	-0.2	-0.7	-0.5	-0.6	-0.5	-0.4	-0.2	1.9	-0.1	-0.3	-0.3	-0.5
Central America	-1.0	0.1	0.2	-0.0	0.1	0.3	-0.1	0.0	-12.1	0.2	-0.2	0.2	0.4
Caribbean	-1.6	0.5	-0.8	0.2	0.2	0.5	-0.1	0.2	-10.6	0.3	0.1	0.3	0.6
EU	-1.4	0.4	0.7	-0.5	-0.2	-0.0	-0.1	0.1	0.8	-0.0	0.2	0.1	0.3
Rest of EFTA	-0.2	7.8	11.4	3.8	2.8	4.1	1.1	3.4	-15.7	0.3	0.2	0.7	1.6
East Europe	-0.3	0.3	0.5	0.1	-0.1	0.1	-0.5	0.2	-8.4	-0.0	0.1	0.2	0.4
Rest of Europe	-0.8	0.6	1.3	0.8	1.1	0.7	0.4	0.5	-8.9	0.1	1.2	0.6	1.2
Rest of Soviet Union	-0.3	0.3	0.2	0.3	0.2	0.7	0.1	0.2	-18.6	0.1	-2.6	0.1	0.2
Western Asia	-0.7	0.3	0.5	0.3	-0.0	0.4	-0.1	0.2	-7.4	-0.1	-0.6	0.0	0.1
Northern Africa	-0.6	0.2	-0.5	-0.5	-0.3	-0.2	-0.2	-0.1	4.8	-0.1	0.1	-0.0	-0.1
Western Africa	-27.7	-3.6	-66.0	-57.2	-40.7	-43.1	-22.0	-13.2	111.2	-4.3	-9.3	-0.3	-0.7
Central Africa	-2.3	1.9	-4.7	-4.2	-4.5	-8.0	-2.0	-2.0	84.4	0.6	0.0	-0.4	-0.7
South Central Africa	-0.9	0.1	-0.9	-1.0	-0.8	-1.0	-0.9	-0.2	4.0	-0.1	-0.2	-0.0	-0.0
Eastern Africa	-2.1	-0.4	-4.1	-3.6	-3.4	-2.3	-1.6	-1.1	7.3	-0.3	-0.9	-0.1	-0.1
Southern Africa	-1.6	-0.4	-2.7	-2.6	-1.3	-1.6	-1.1	-0.7	4.5	-0.2	-1.3	-0.7	-1.2
ROW	-0.7	-0.1	-0.5	-0.6	-0.9	-0.4	-0.3	-0.4	-0.7	-0.1	-0.4	-0.3	-0.4

Table 12: Change in output due to changes in livestock yields (percent change)

Region	Rice	Wheat	Coarse grains	Fruits/vegetables/nuts	Oilseeds	Sugar crops	Plant-based fibers	Other crops	Meat/livestock	Extraction	Processed food	Manufacturing	Services
Oceania	-2.8	-8.4	-4.5	-2.9	-4.1	-0.3	-10.8	-2.9	-0.6	-0.1	-0.5	-0.0	-0.1
East Asia	-6.4	-3.4	-1.9	-3.1	-3.8	0.3	-3.0	-3.4	-0.5	-0.0	-0.6	0.2	0.4
Southeast Asia	-2.8	-3.5	-2.7	-3.1	-2.9	-1.7	-3.5	-3.2	-0.2	-0.0	-0.7	0.2	0.3
South Asia	-9.5	-5.7	-13.0	-9.3	-4.6	-19.7	-5.2	-8.5	0.0	0.7	-3.0	0.2	0.4
USA	-8.0	-5.3	-4.4	-4.5	-3.8	-10.4	-4.2	-6.1	-1.4	0.0	-0.2	0.2	0.3
Rest of North America	-9.3	-4.6	-3.6	-4.7	-3.6	-3.8	-14.2	-4.7	-0.6	-0.1	-0.4	0.1	0.0
South America	-4.9	-7.4	-4.4	-4.6	-4.3	-2.2	-3.3	-4.1	-1.3	-0.1	-0.8	0.1	0.1
Central America	-4.3	-3.0	-4.3	-4.2	-3.7	-4.3	-3.6	-3.9	-0.7	-0.2	-0.7	0.1	0.2
Caribbean	-5.0	-2.6	-4.8	-4.0	-4.1	-5.6	-3.7	-4.1	-0.4	0.0	-0.4	0.2	0.3
EU	-4.4	-5.2	-5.3	-4.6	-3.7	-2.2	-4.9	-3.0	-0.8	-0.4	-0.2	0.3	0.4
Rest of EFTA	-2.5	-5.2	-9.5	-6.8	-5.5	-15.5	-3.0	-4.6	-0.4	-0.3	-0.1	0.2	0.3
East Europe	-4.4	-5.2	-3.7	-3.4	-3.8	-5.4	-2.6	-2.6	-1.0	-0.2	-0.8	-0.0	0.0
Rest of Europe	-4.7	-5.4	-5.2	-5.7	-8.7	-5.8	-3.8	-6.0	-0.8	0.2	-0.1	0.3	0.4
Rest of Soviet Union	-2.3	-4.3	-2.1	-2.3	-3.1	-0.3	-2.1	-2.4	-1.0	-0.1	-0.2	0.1	0.1
Western Asia	-4.9	-4.1	-4.0	-4.0	-4.0	-1.6	-2.4	-3.5	-0.8	-0.1	-0.8	0.1	0.2
Northern Africa	-3.0	-4.8	-18.4	-11.3	-1.7	3.1	0.3	-1.0	0.5	-3.8	0.6	1.3	2.9
Western Africa	-10.3	-5.2	-3.6	-6.1	-5.4	-3.5	-3.4	-5.3	0.4	0.8	-0.6	0.1	0.1
Central Africa	-2.6	-1.8	-0.4	-0.3	-1.5	-0.3	-1.6	-2.4	-0.3	-0.2	-0.0	0.1	0.2
South Central Africa	-6.5	-3.7	-6.2	-5.8	-4.3	-2.1	-4.2	-3.0	-1.0	-0.2	-0.5	0.1	0.1
Eastern Africa	-47.2	-14.1	-99.1	-97.0	-72.4	-22.0	-60.1	-17.1	-3.4	-2.2	-4.6	0.6	1.1
Southern Africa	-15.1	-7.9	-18.8	-10.6	-8.7	-3.0	-7.8	-7.8	-0.9	-0.2	-1.3	0.1	0.1
ROW	-1.5	-2.9	-1.3	-1.4	-1.7	-0.7	-1.6	-2.3	-0.7	-0.2	-0.8	-0.3	-0.6

Table 13: Change in prices due to changes in land types (percent change)

The output changes in the crops scenario (using the yield changes as presented in Table 4) shown in Table 3 for the world and in Table 7 for each region indicate that the implication of the projected changes in crop yields due to climate change is small relative to the changes in baseline. The greatest reduction in output of 2.5 percent is observed in the meat/livestock sector, driven by the output changes of fed grains. The output of grains falls between 1.2 percent for coarse grains and 0.7 percent for rice. Production of fruits and vegetables falls by 1.3 percent. Even though the global output changes are small, regional results vary noticeably. The USA has a decrease in coarse grains production (where corn is embedded) of 10.9 percent; but several other other major producers (East Asia, the EU, and Eastern Europe) have an increase. In fact, despite the global decline in other agriculture production in the crops scenario, there are many major producers who have increases in their production. There are also decreases in agricultural production across many crops in African regions. This ranges from a decrease of 3.9 percent for wheat for Eastern Africa to a 53.5 percent reduction in wheat production in Central Africa. This indicates that crop yield impacts of climate change could affect some of the poorest regions in the world.

The livestock scenario is also quite mixed in terms of sectors and their change in production. Several crops (coarse grains, fruits/vegetables/nuts, oil seeds, and sugar crops) all experience a decrease in production; the change in meat/livestock is also negative. But, the change is mixed depending on the region (8). Data from Table 4 highlighted that Western Africa is the region with the largest decrease in productivity—they are also the region that has the largest decrease in meat/livestock production (at 46.6 percent). Other regions in Africa also had decreases in livestock productivity, and they all also have a decrease in meat/livestock production in this scenario. In total, In total, like in the crops scenario, Africa is estimated to be the most vulnerable and hardest hit. This is supported by a general consensus among scientists that tropical and arid regions such as in Africa will be hardest hit by climate change in the coming decades, especially the productivity of both crops and livestock systems (Kikstra et al. 2022).

The final individual scenario is the land scenario—i.e., shifting AEZs. In this scenario, all agricultural sectors have an increase in production. This is at the expense of manufacturing and services—i.e., resources other than land (labor and capital) move to agriculture. But, the changes in production tend to be modest—in the 0.50 to 2 percent range. Almost all regions (Table 9) have an increase in total production, the main exception is Eastern Africa (who has a 72.2 percent decrease in manufacturing).

5.2 Changes to Prices

The other CGE result that we present are changes in prices, and we present them by scenario as was done for production (Table 14). Starting with the baseline, some agricultural sectors have price increases, the largest is for fruits/vegetables/nuts—which could be a function of increased income (although, meat/livestock—the other sector that consumers switch consumption to as incomes rise, has a decrease in price). More than half (12 of the 22 regions) actually have a decrease in the price of fruits/vegetables/nuts (Table 10), but large price increases in South Asia and in Africa lead to the overall price increase. Prices for manufacturing and services decrease by the most, likely a result of these sectors experiencing large increases in productivity and production.

For the crops scenario (and all the other individual scenarios), the impacts to prices are of a smaller magnitude than those for the baseline. Many agricultural sectors have a decrease in global prices, but there is an increase in coarse grains. This could be a function of the yield decrease for the USA causing global competition to increase—recall that coarse grains production increases, despite the overall decrease in global yields.

For the livestock scenario, price changes tend to be mixed, although there is a 0.9 percent increase in the global price of meat/livestock. But, again examining Western Africa, the results indicate a dramatic increase in the meat/livestock price of 111.2 percent. The other African region with a large decrease in production also has a large increase in the meat/livestock price of 84.4 percent. Thus, while the global price increase is only 0.9 percent, there are clearly some regions which are more impacted than others. These projected price increases in some of the poorest regions in Africa will likely increase the incidence of food insecurity in the region. The incidence of malnutrition, in particular, may erode further as prices for more nutritious foods, such as livestock and fruits/vegetables/nuts as noted above, also rise on the continent.

Finally, shifting land use leads to decreases in the price of all agricultural sectors. That is, climate change is

Table 14: Percent Change in Global Prices

Region	Baseline	Crop Yields	Livestock productivity	Land shifts	Total
Rice	33.3	-5.2	-1.0	-7.2	21.0
Wheat	-4.0	-6.5	0.4	-5.0	-15.4
Coarse grains	74.5	12.8	-4.4	-12.4	74.9
Fruits/vegetables/nuts	79.6	-3.2	-4.3	-9.5	67.0
Oilseeds	30.6	-7.8	-1.6	-8.3	14.6
Sugar crops	-0.5	-0.1	-0.9	-4.3	-4.8
Plant-based fibers	22.4	1.2	-1.3	-5.5	18.1
Other crops	-18.6	-3.3	-0.1	-4.2	-26.1
Meat/livestock	-20.8	1.1	0.9	-0.8	-20.6
Extraction	-50.2	-0.1	-0.1	-0.2	-50.4
Processed food	-42.3	-0.5	-0.1	-0.7	-43.6
Manufacturing	-82.4	0.0	0.0	0.2	-82.1
Services	-65.4	0.1	0.1	0.3	-65.0

shifting where land is being grown, but farmers are able to adapt and produce enough such that prices do not increase. The decrease in agricultural prices does lead to a small decrease in the price of non-agricultural products in the lands scenario as resources are moved out of agriculture into other sectors.

The final column presents the changes across all the scenarios. These price changes are, again, heavily influenced by the changes from the baseline. That is, the signs never differ (i.e., those that have an increase in price in the baseline also have an increase in the total scenario, and vice versa). And any magnitude in a price increase from the baseline is often softened in the total scenario, the exception is for coarse grains, which has an increase from the crops component. Those sectors that have a decrease in price from the baseline, however, tend to have stronger decreases in the total scenario—mainly a function of decreasing prices from switching land.

6 Concluding Remarks

Climate change is expected to greatly impact the global economy in the future, but uncertainty abounds in the magnitude of those impacts. In terms of what sectors could be the most impacted by climate change, agriculture is at the forefront as changes in precipitation and temperatures directly affect growing conditions. In addition, the population is expected to grow—and to become richer, leading to the need to grow more food, especially livestock products. The literature has considered how agriculture could be impacted, but the approach is often to consider only some aspects of a changing climate. That is, some research has looked at potential crop yields, while others have examined potential changes to livestock production. In this work, we attempt to provide a complete picture of what agriculture might look like in 2050. To do so, we combine information on crop and livestock yield/productivity changes with estimates of what land might look like by shifting AEZs. We use these supply changes in a computable general equilibrium (CGE) model, along with potential demand changes to estimate the impacts of climate change on agriculture. Given that Africa is likely to be hardest hit by climate change as we have shown in this study and supported by others (Kikstra et al. 2022), in addition to having a large population of resource-poor and vulnerable populations, we also pay some attention to how the region may be adversely affected in terms of agricultural production and food prices.

Overall, our results at the global level indicate that, at least up to 2050, the agricultural sector is generally resilient to climate change so long as there are increases in agricultural productivity. As a result, every agricultural sector is estimated to have an increase in production. There are, however, some deviations by sector when some of the individual scenarios are considered, such as changes in livestock productivity from climate change. The model estimates increases in agricultural production when all the scenarios are implemented that range between 15.67 percent for sugar crops to 68.34 percent for processed food. Whether these changes are enough to keep pace with a growing, and richer, population will remain to be seen. Using projections from CEPII, we assume a change in population of 11.10 percent and 141.70 percent for GDP. Every agricultural sector has a change in production that is larger than the population change, but smaller than the GDP change. Thus, if consumers switch food demand away from grains to fruits/vegetables/nuts and meat/livestock, there could be difficulty in meeting demand.

While our results indicate that global production increases for every agricultural sector, there are differences across regions. In particular we find that many regions in Africa could experience decreases in production, which could impact food availability if there are no policy changes. In particular, the production of meat/livestock in Western and Central Africa is the most negatively impacted. These are regions where people depend on livestock not just for food, but as a source of income and wealth. Future work could examine more countries in detail (i.e., disaggregate some of these African regions) to determine what countries could be the most negatively impacted from climate change.

We also find that agricultural price changes are mixed, with wheat estimated to have a decrease in price from crop yield improvements, while coarse grains and fruits/vegetables/nuts are estimated to have increases larger than 50 percent. Coarse grains are impacted by yield decreases, while the increase in the price of fruits/vegetables/nuts comes from wealthier consumers. Again we find that those most impacted from price increases are regions in Africa, such as Western and Central Africa.

One final point is that our results hinge heavily on the productivity assumptions. However, productivity is not some manna from heaven, but is a function of investment in research and development (R&D). For agriculture, Fuglie (2018) notes that total agricultural R&D spending will likely need to grow faster than the desired rate of agricultural output growth due to limits on the transferability of agricultural technologies and also the need for research to keep productivity from falling. Thus, major investments might be needed to maintain the ability to feed a growing population while acknowledging that mitigating adverse climate change effects have a major role to play in the future expenditures. In his 2021 work, Fuglie (Fuglie 2021) notes that recent evidence (e.g., Ortiz-Bobea et al. 2021) highlights that climate change has effectively brought back into play the argument from Thomas Malthus—that population growth would outstrip the ability to supply food to the population.

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A Appendix

Table A.1: Percentage change in herbaceous biomass on rangelands between 2017 and 2050

Region	Mean (%)	Min. (%)	Max. (%)
Africa			
Eastern Africa	-9.23	-13.10	-5.55
Middle Africa	-15.33	-18.01	-10.37

Region	Mean (%)	Min. (%)	Max. (%)
Northern Africa	-18.45	-21.87	-15.94
Southern Africa	-19.77	-25.76	-13.81
Western Africa	-34.20	-41.88	-25.16
Americas			
Caribbean	12.60	-4.92	51.02
Central America	-11.63	-19.87	-5.32
Northern America	21.69	17.22	30.36
South America	-1.96	-4.79	0.06
Europe			
Eastern Europe	24.37	14.70	32.96
Northern Europe	35.49	27.47	41.52
Southern Europe	-6.67	-10.05	-3.52
Western Europe	1.99	0.22	5.49
Asia			
Central Asia	15.39	5.08	22.14
Eastern Asia	11.04	5.26	15.48
South-Eastern Asia	-6.11	-8.48	-1.08
Southern Asia	9.61	4.53	14.78
Western Asia	8.00	4.80	12.98
Oceania			
Australia and New Zealand	-2.61	-10.25	6.43
Melanesia	0.32	-2.99	3.51
Global	-1.82	-5.90	0.34

Table A.2: Meat Productivity Results by Region, Percentage Change from 2017 to 2050

Region	Mean (%)	Min. (%)	Max. (%)
Africa			
Eastern Africa	-3.40	-6.58	0.38
Middle Africa	-31.87	-36.16	-25.93
Northern Africa	-27.33	-32.75	-23.55
Southern Africa	-7.74	-11.45	-5.18
Western Africa	-36.37	-44.99	-27.01
Americas			
Caribbean	12.60	-4.92	51.02
Central America	-3.72	-11.96	-1.45
Northern America	1.01	-2.79	3.02
South America	-1.24	-2.75	-0.16
Europe			
Eastern Europe	8.34	1.21	12.81
Northern Europe	19.31	-0.56	44.11
Southern Europe	-13.65	-17.20	-10.67
Western Europe	-0.36	-4.18	5.95
Asia			
Central Asia	14.89	8.97	20.05
Eastern Asia	8.69	7.07	10.24
South-Eastern Asia	-2.41	-7.07	3.28
Southern Asia	7.97	3.53	12.52
Western Asia	5.02	3.67	5.82
Oceania			
Australia and New Zealand	-3.74	-9.43	2.12

Region	**Mean (%)**	**Min. (%)**	**Max. (%)**
Melanesia	4.37	0.22	6.83
Global	-3.77	-5.67	-2.63

Table A.3: Milk Productivity Results, Percentage Change from 2017 to 2050

Region	**Mean (%)**	**Min. (%)**	**Max. (%)**
Africa			
Eastern Africa	-4.97	-8.87	-0.98
Middle Africa	-31.87	-36.17	-25.94
Northern Africa	-37.51	-47.69	-31.65
Southern Africa	-7.74	-11.45	-5.18
Western Africa	-36.37	-44.99	-27.01
Americas			
Caribbean	12.60	-4.92	51.02
Central America	-3.92	-12.22	-1.70
Northern America	1.02	-2.79	3.02
South America	-1.24	-2.75	-0.16
Europe			
Eastern Europe	8.96	1.70	13.42
Northern Europe	19.31	-0.56	44.11
Southern Europe	-13.31	-16.85	-10.39
Western Europe	-0.36	-4.18	5.95
Asia			
Central Asia	14.80	8.93	19.98
Eastern Asia	5.75	3.43	9.36
South-Eastern Asia	-2.39	-6.66	3.08
Southern Asia	1.79	-0.47	7.82
Western Asia	1.07	-1.84	2.95
Oceania			
Australia and New Zealand	-3.68	-9.33	2.13
Melanesia	4.37	0.22	6.83
Global	-6.98	-10.01	-4.06

Region	Components
Oceania	aus,nzl,xoc
East Asia	chn,hkg,jpn,kor,mng,twn,xea
Southeast Asia	brn,khm,idn,lao,mys,phl,sgp,tha,vnm,xse
South Asia	bgd,ind,npl,pak,lka,xsa
USA	usa
Rest of North America	can,mex,xna
South America	arg,bol,bra,chl,col,ecu,pry,per,ury,ven,xsm
Central America	cri,gtm,hnd,nic,pan,slv,xca
Caribbean	dom,jam,pri,tto,xcb
EU	aut,bel,bgr,hrv,cyp,cze,dnk,est,fin,fra,deu,grc,hun,irl,ita,lva,ltu,lux,mlt,nld,pol,prt,rou,svk,svn,esp
Rest of EFTA	gbr,che,nor,xef
East Europe	srb,alb,blr,rus,ukr,xee
Rest of Europe	xer
Rest of Soviet Union	kaz,kgz,tjk,xsu
Western Asia	arm,aze,geo,bhr,irn,irq,isr,jor,kwt,lbn,omn,pse,qat,sau,syr,tur,are,xws
Northern Africa	egy,mar,tun,xnf
Western Africa	ben,bfa,cmr,civ,gha,gin,nga,sen,tgo,xwf
Central Africa	xcf
South Central Africa	xac
Eastern Africa	eth,ken,mdg,mwi,mus,moz,rwa,sdn,tza,uga,zmb,zwe,xec
Southern Africa	bwa,nam,zaf,xsc
ROW	xtw

Table A.4: Regional aggregation

Commodity	Components
Rice	pdr
Wheat	wht
Coarse grains	gro
Fruits/vegetables/nuts	v_f
Oilseeds	osd
Sugar crops	c_b
Plant-based fibers	pfb
Other crops	ocr
Meat/livestock	ctl,oap,rmk,wol,cmt,omt
Extraction	frs,fsh,coa,oil,gas,oxt
Processed food	vol,mil,pcr,sgr,ofd,b_t
Manufacturing	tex,wap,lea,lum,ppp,p_c,chm,bph,rpp,nmm,i_s,nfm,fmp,ele,eeq,ome,mvh,otn,omf
Services	ely,gdt,wtr,cns,trd,afs,otp,wtp,atp,whs,cmn,ofi,ins,rsa,obs,ros,osg,edu,hht,dwe

Table A.5: Commodity aggregation